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Abstract

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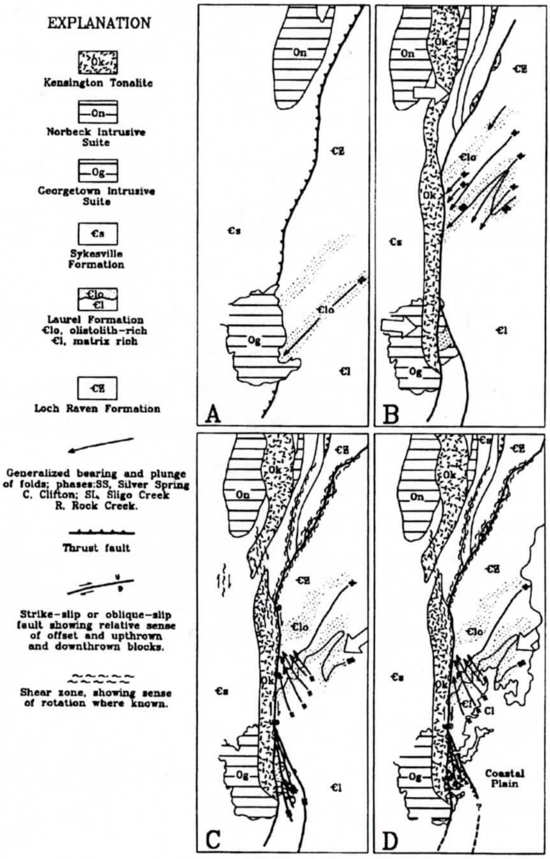

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EDITOR'S PAGE

Number Three

The first issue of Southeastern Geology was published in the spring of 1959. Since that time 639 articles have been published on just about every aspect of the geological sciences in the southeastern states. With this issue I am introducing a first for this journal — a book review. I hope that you will take time to look at the review and perhaps even buy a copy of the book. It is the story of Vanderbilt's Department of Geology. Many will find parallels with other universities where they teach or have attended.

I invite other authors to submit their recent books dealing with earth science in the southeast. We hope that book reviews can become a regular part of this journal.

If you are preparing a manuscript on any phase of the geology, hydrology or environmental geology of the southeast, I encourage you to submit it to this journal. The manuscript will be given a fair review by two peer critical readers as promptly as possible.

Duncan Heron

SOUTHEASTERN GEOLOGY
V. 37, No. 3, February 1998, p. 115-140

STRUCTURE, AGE, AND TECTONIC SETTING OF A MULTIPLY REACTIVATED SHEAR ZONE IN THE PIEDMONT IN WASHINGTON, D.C., AND VICINITY

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ABSTRACT

The Rock Creek shear zone is the dominant tectonic feature in the Piedmont in Washington, D.C. and adjacent parts of Maryland, has an exposed length of 25 km, and a width of up to 3 km. The shear zone is characterized by a complicated composite fabric produced by the imposition of both ductile and brittle structures as well as the reactivation, transposition, and folding of older structures during subsequent antithetic displacement. At least five main types of structural elements are discernible and include: 1) relict, medium- to coarse-grained mylonitic foliation and related structures produced by sinistral shearing under at least middle amphibolite facies conditions; 2) a ductile fault zone having an apparent sinistral displacement of at least several km and an unknown, but possibly significant component of upward throw of the east wall; 3) pervasive, fine-grained ultramylonitic foliation associated with quartz ribbons and late oblique shear bands, generated by dextral shearing under thermal conditions that appear to have progressed from middle greenschist to sub-greenschist (semi-brittle); 4) a system of oblique-(west wall up) and dextral-slip faults localized chiefly within a tectonic mélange at the junction of two major strands, and whose motion spanned the ductile-brittle transition; and 5) a system of post-Cretaceous thrust faults that cut Coastal Plain rocks as young as Quaternary as well as the previously deformed crystalline rocks.

The first two sets of structures are of probable Ordovician age and are thus believed to coincide with the Taconic event, which produced regional middle to upper amphibolite facies metamorphism, widespread plutonism, and extensive southwest-vergent fold phases in this area. In contrast, the dextral shearing and faulting were generated during final thermal cooling and represent the latest Paleozoic penetrative deformation that affected this area. They are very likely Alleghanian because of their great similarity to other better-dated Alleghanian structural features in the Maryland and Virginia Piedmont.

INTRODUCTION

Fault zones that record complex histories of multiple reactivations are recognized from diverse locations within the Appalachians (e.g., Drake and others; 1989; Hatcher and others, 1989). Within the Piedmont, these zones of high strain commonly form significant local or regional tectonic boundaries separating contrasting lithotectonic assemblages that experienced different histories prior to their assembly, and (or) that responded differently to subsequent deformations due to different bulk rock properties. Such tectonic junctures can sometimes contain a relatively complete, though isolated, record of deformation events and processes that have affected rocks on both sides of the shear zone; the fabric and mineral assemblages within

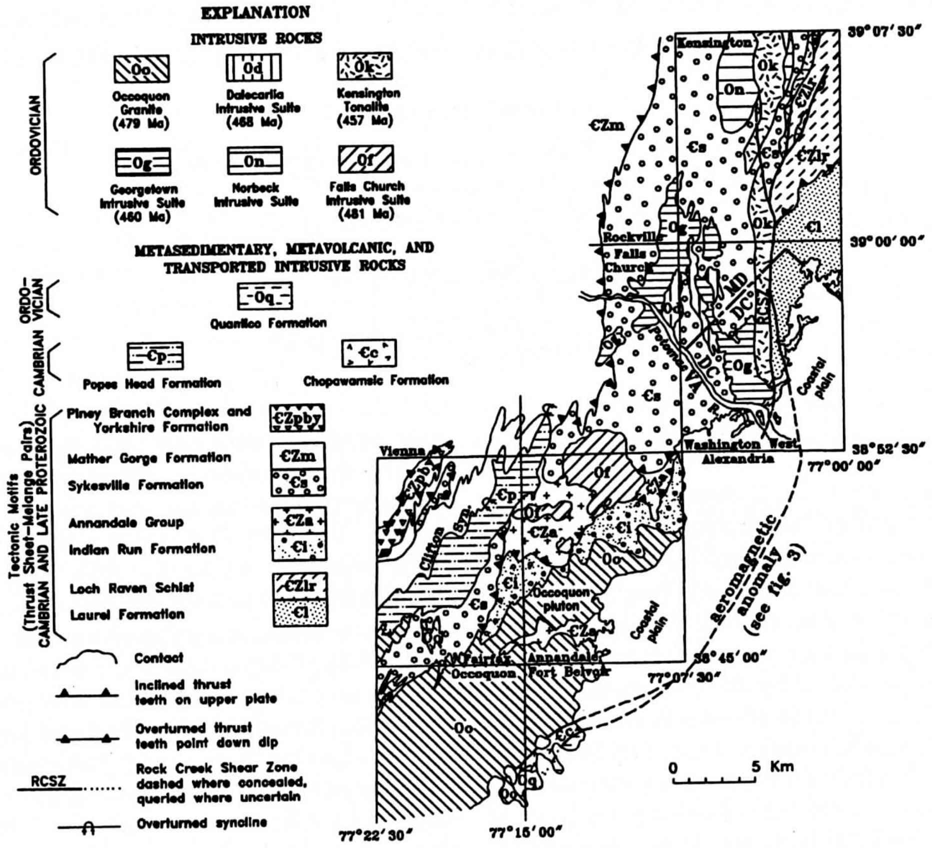

Figure 1. Generalized geologic map of Washington, D.C. and vicinity, showing regional setting of the Rock Creek Shear Zone, mélange pairs of the Potomac terrane, trace of aeromagnetic anomaly beneath the Coastal Plain region, and locations of quadrangles mentioned in text. Sources of data, by 7.5-minute quadrangle: Fairfax (Drake,1986); Annandale (Drake and Froelich, 1986); Vienna (Drake and Lee, 1989); Falls Church (Drake and Froelich, 1997); Washington West (Fleming and others, 1994); Kensington (Drake, in press); Occoquon and Fort Belvoir (Seiders and Mixon, 1981), A.A. Drake, Jr. (unpublished data); Rockville and Alexandria, A.A. Drake, Jr. (unpublished data).

often represent the microcosm of regional tectonothermal history, and may provide the structural and temporal linkage between seemingly disparate events and rocks.

A well-developed shear zone containing evidence for multiple episodes of deformation was recently recognized near the eastern edge of the Piedmont in the District of Columbia and adjacent parts of Maryland (Fleming and others, 1992; 1994; Drake, in press; Figure 1). The shear zone has a known length of at least 25 km and has affected rocks across a zone as much as 3 km wide. Structural effects evident at scales ranging from microscopic to regional were generated during at least three main episodes of deformation that occurred under vastly different tectonothermal conditions. The episodic history resulted in a complex, composite structure characterized by reactivation, reuse, and reorientation of older structures as well as imposition of a variety of structural features produced by both ductile and brittle deformation. The shear zone is well exposed in and near Rock Creek Valley in the District of Columbia, and was termed the Rock Creek shear zone (RCSZ) by Fleming and others (1992; 1994).

This paper summarizes the regional setting and major structural elements of the RCSZ, with emphasis on the progressive ductile deformation of affected metasedimentary and intrusive rocks, and on the nature, kinematics, and relative timing of the individual structural elements that have been superposed to produce the composite fabric that typifies the RCSZ. Resolution of these elements and their relationships to structures and mineral assemblages of adjacent rock units allows the episodic development of the shear zone to be related to regional tectonic history, and affords a basis for broadly constraining the ages of the different episodes of deformation.

REGIONAL GEOLOGIC SETTING

The District of Columbia (for brevity, referred to hereafter as "D.C.") straddles the Fall Zone that separates crystalline rocks of the Piedmont on the west from poorly consolidated sedimentary rocks of the Atlantic Coastal Plain to the east. The RCSZ and adjacent rock units are well exposed along the Fall Zone in D.C. and adjoining counties to the north in Maryland; the shear zone and its wall rocks pass beneath the Coastal Plain sediments near the Potomac River in downtown D.C. and extreme northern Virginia.

The crystalline rocks of the D.C. area range in age from Late Proterozoic(?) and/or Cambrian to late Ordovician. Recent work suggests that the majority of metasedimentary rocks in this region, as well as some large ultramafic bodies, constitute a stack of thrust sheets, each of which tectonically overlies its own precursory mélange (Drake and Lyttle, 1981; Drake and Morgan, 1981; Drake, 1985a; 1987; 1989; Horton and others, 1989; Fleming and others, 1994; Drake and Froelich, 1986; 1997). Each precursory mélange characteristically contains fragments of metasedimentary rocks derived from the overlying thrust sheet, in addition to clast types found in all of the mélanges, such as quartz pebbles, amphibolite, and various ultramafic rocks. Metasedimentary and ultramafic fragments range in size from microscopic to km-scale, and generally increase in abundance toward the contact with the overlying thrust sheet.

Several such lithotectonic assemblages, referred to informally as "tectonic motifs" (Drake, 1985b; 1989), have been mapped in the D.C.-Maryland-northern Virginia Piedmont (Figure 1), and two of these are present in the immediate vicinity of the RCSZ: 1) the Mather Gorge-Sykesville motif; and 2) the Loch Raven-Laurel motif. The former consists of a thick sequence of high-energy turbidites (Mather Gorge Formation) that were polydeformed, progressively metamorphosed to uppermost amphibolite facies, locally migmatized, and partially retrograded to phyllonites before being emplaced on the Sykesville Formation (Drake and Morgan, 1981; Drake, 1989; Becker and others, 1993). The Sykesville is a massive, medium-grained, quartzofeldspathic submarine slide deposit possibly as much as 10 km thick that contains abundant fragments of the polydeformed turbidite sequence. The Sykesville is choked with fragments of phyllonitized migmatites within a few hundred meters of the tectonically overlying Mather Gorge rocks. In contrast, the Loch Raven-Laurel motif consists of a sequence of well-bedded, biotitic metaarenite and biotite-rich schist (Loch Raven Formation) thought to have been deposited in a low-energy marine basin (Hopson, 1964; Crowley, 1976; Fleming and others, 1994; Drake, in press). The lower, metaarenite part of this sequence was also informally termed the "Northwest Branch formation" (Fleming and others, 1994; Drake, in press); for simplicity, it is here included with the Loch Raven. The stratified rocks of the Loch Raven tectonically overlie a coarse-grained, locally gneissic, micaceous, quartzofeldspathic mélange (Laurel Formation) that contains numerous olistoliths of prograde metaarenite and biotitic schist. The upper several hundred meters of the mélange constitute a distinct olistolith-rich unit that commonly contains 50 to 75% fragments of Loch Raven rocks. Unlike the Sykesville, individual submarine slides and discrete slide surfaces are evident at places in the Laurel, especially in the olistolith-rich upper unit. The total thickness of the Laurel is unknown because its bottom is not exposed in this area, but it is probably on the order of several

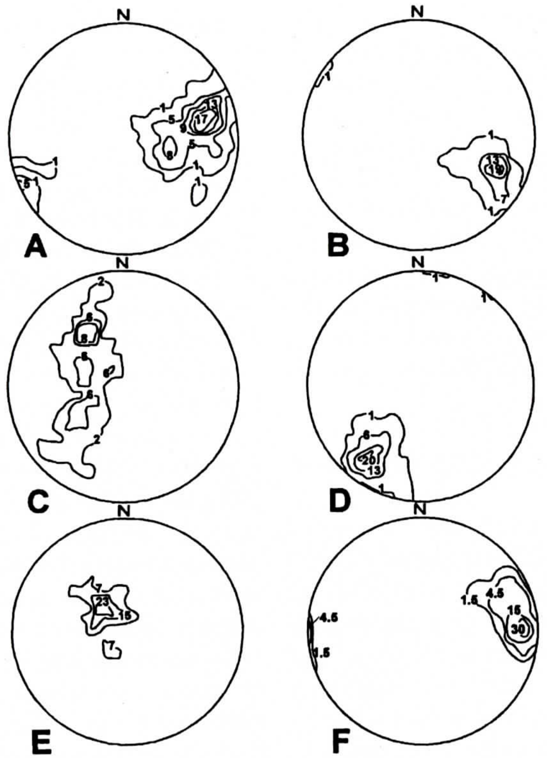

Figure 2. Equal area projections (lower hemisphere) of some structural elements in and near the RCSZ. Contours represent percent of data per one percent area. A) 96 poles to foliation in the Sykesville Formation west of the RCSZ. Contours at 17, 13, 9, 5, and 1 percent. B) 48 poles to Sligo Creek foliation in the Laurel Formation east of RCSZ. Contours at 19, 13, 7, and 1 percent. C) 49 quartz rods in the Kensington Tonalite along west wall of RCSZ. Plot is a girdle with maximum at 42°N32°W. Contours at 8, 6, and 2 percent. D) 55 mineral and clast elongation lineations lying within Sligo Creek foliation in the Laurel Formation east of the RCSZ. Contours at 20, 13, 6, and 1 percent. E) 25 axes of folds of foliation in the Kensington Tonalite. Contours at 23, 15, and 7 percent. F) 68 poles to mylonitic foliation in the Laurel Formation along east side of RCSZ. Contours at 30, 15, 4.5, and 1.5 percent.

km.

The metasedimentary rocks in the D.C. area are intruded by several small to medium-size plutons of predominantly tonalitic composition (Figure 1). These bodies are part of an extensive Ordovician magmatic arc that includes the Occoquon Granite (Seiders and others, 1975), Clarendon Granite (Drake and Fleming, 1994), and Falls Church Intrusive Suite (Drake and Froelich, 1986; 1997) of northern Virginia and the Dalecarlia Intrusive Suite in D.C. (Drake and Fleming, 1994). The main intrusive rocks in the Rock Creek area are the Georgetown Intrusive Suite (Fleming and others, 1994), Kensington Tonalite (Cloos and Cooke, 1953; Hopson, 1964; Fleming and others, 1994), and Norbeck Intrusive Suite (Hopson, 1964; Drake, in press). The Georgetown and Norbeck are virtually identical and consist chiefly of mafic, quartz-rich, biotite-hornblende tonalite with lesser amounts of quartz gabbro and quartz diorite, and minor amounts of pyroxenite. Zircons from the Georgetown in southern Rock Creek Valley yield an apparent single-crystal age of crystallization of 465± 5 Ma, whereas conventional data yield a concordant age of 466± 3 Ma (J. Aleinikoff, U.S.G.S., written communication, 1994). The Kensington Tonalite consists of leucocratic muscovite-biotite tonalite, much of which has been moderately to severely sheared. Elongate,

Table 1. Fold phases in the Washington West and Kensington 7.5-minute quadrangles.

Phase	Trend	Foliation	Lineation	Style
Clifton	NNE to NNW	Crystallization foliation	Mineral lineation	Tight, upright to isoclinal, over-turned; fold earlier foliations in Sykesville Formation
Rock Creek	NW	Spaced schistosity or cleavage	Crenulations	Tight, upright to isoclinal, overturned; fold bedding, schistosity, and earlier fold axes in rocks of the Loch Raven thrust sheet and foliations and earlier fold axes in Laurel Formation
Sligo Creek	NE	Crenulation schistosity in rocks of Loch Raven thrust sheet and crystallization foliation in Laurel Formation	Mineral lineation	Tight, upright to isoclinal, overturned; fold bedding and schistosity in rocks of the Loch Raven thrust sheet, and Silver Spring foliation and individual slide surfaces in Laurel Formation
Silver Spring	NE	Crystallization foliation in Laurel Formation	Mineral lineation	Tight, upright to isoclinal, overturned; fold individual slide surfaces in Laurel Formation

north-trending bodies of Kensington Tonalite form most of the west wall of the RCSZ. The Kensington intrudes the Georgetown at several localities in Rock Creek Park. Zircons from the Kensington adjacent to the shear zone yield an apparent single-crystal age of 460± 4 Ma, whereas conventional zircon data yield a discordant age of about 472 Ma (J. Aleinikoff, U.S.G.S., written communication, 1994). All of these plutons exhibit evidence for deformation in the form of secondary foliations, crushing and recrystallization of grains, development of localized retrograde mineral assemblages, well-developed quartz-rod lineations, and localized folding of foliations. Such features are less conspicuous in the Georgetown, which commonly exhibits well-preserved magmatic flow structures and coarse, hypidiomorphic-granular texture, whereas much of the Kensington is intensely sheared and recrystallized and occurs as strongly lenticular plutons.

The D.C. area has long been recognized as one of strong structural convergence, reflected in the marked culmination of rock units that occupy much broader areas in the Maryland Piedmont to the north, and by a concentration of elongate, broadly concordant intrusions. The most common interpretation is that the area lies at the southern nose of a broad regional structure termed the "Baltimore-Washington anticlinorium" (e.g., Fisher, 1963. 1970; Hopson, 1964), whose convergent limbs were ultimately defined by the Laurel and Sykesville Formations and adjacent "Wissahickon" rocks. The classical interpretation of this structure in the D.C. area thus hinges on the presumed stratigraphic equivalence of these two mélanges. As far as is known, however, no fragments of Mather Gorge rocks are present in the Laurel Formation, whereas no Loch Raven olistoliths have been observed from the Sykesville. The two tectonic motifs adjacent to the RCSZ also exhibit strikingly different fold patterns whose contrasting orientations help to amplify the sharp structural boundary that separates them (Figures 2 and 3; Table 1). The Loch Raven-Laurel motif contains two prominent, coaxial sets of southwest-plunging folds. These fold phases are referred to as Silver Spring and Sligo Creek folds (Fleming and others, 1994), and are locally refolded about a third, less prominent set of northwest-trending "Rock Creek" folds. The southwest-trending folds are the dominant structural feature east of the shear zone and have imparted a prominent southwesterly grain to planar and linear mesoscopic structures throughout that area. These folds are particularly evident in the distribution of the upper, olistolith-rich zone of the Laurel Formation, and the contact with its overlying thrust sheet, in the northern part of Rock Creek Park and areas just to the east.

In contrast, Mather Gorge-Sykesville rocks exhibit more northerly trending folds that consistently face west. These folds are most apparent in the well-bedded Mather Gorge rocks

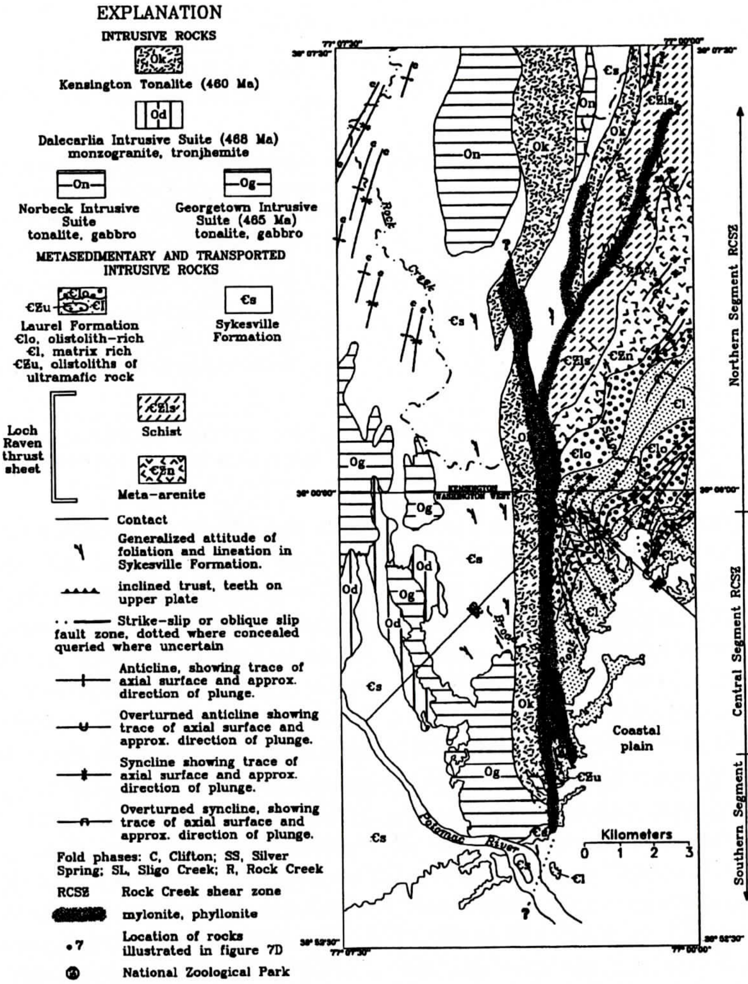

Figure 3. Simplified geologic map of the Washington West and Kensington 7.5-minute quadrangles, showing rock units, structural features, and geographic reference points in the vicinity of the Rock Creek Shear Zone. Same data sources as figure 1.

somewhat south and west of D.C. proper (Drake and Froelich, 1986; 1997; Drake, 1986; 1989; Drake and Lee, 1989). Paucity of bedded metasedimentary rocks and other distinctive stratigraphic markers in the large area of massive Sykesville Formation immediately west of the shear zone hinders clear identification of fold axes in that area, but the consistent north- to northwest-striking foliations and west- to northwest-plunging linear elements lie at sharp angles to their counterparts in the Laurel (Figure 2). The narrow junction between the two motifs and their contrasting structural elements is, in fact, a zone of extreme high strain, represented along virtually its entire length by the RCSZ, and locally set off by elongate bodies of sheared tonalite.

Coastal Plain deposits consist chiefly of deeply weathered fluvial sand and gravel that are locally interbedded with or are in lateral facies relations with thin to thick units of marine and estuarine clay and diatomaceous silt (Fleming and others, 1994). These deposits range in age from Early Cretaceous through Late Pleistocene but do not record a continuous sedimentary succession in this area. Several extensive

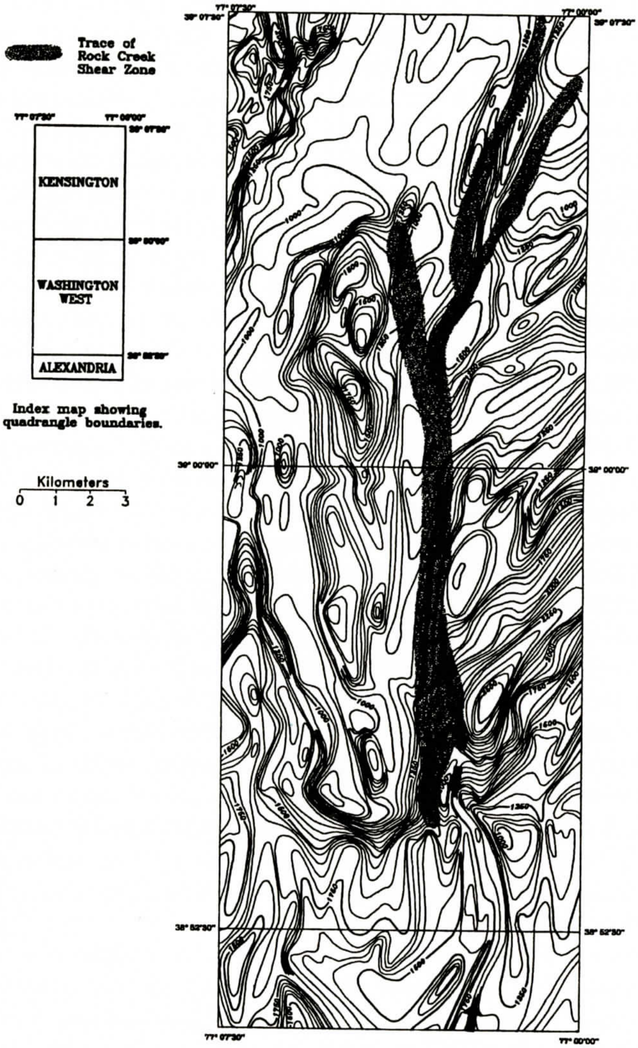

Figure 4. Aeromagnetic map of the Washington West, Kensington, and northern edge of the Alexandria quadrangles. Same scale as figure 3. The prominent curvilinear anomaly (arrows) beneath the coastal plain in Washington, D.C. extends across the Alexandria quadrangle to the south. Kensington data from Bromery, Gilbert, and others (1963). Washington West and Alexandria data from U.S. Geological Survey, unpublished.

outliers of late Tertiary fluvial gravel cap some of the Piedmont ridgetops just west of the Fall Zone. These outliers appear to lie at anomalously greater elevations than their counterparts east of the Fall Zone and thus appear to have been uplifted tectonically. The Fall Zone in the D.C. area has been significantly affected by episodic thrust faulting since the Cretaceous, some of which is localized in a reactivated segment of the RCSZ.

GENERAL DIMENSIONS OF THE SHEAR ZONE

As a whole, the RCSZ is defined by the intersection of several distinct, north-south-trending zones of sheared rocks. These zones of ductile deformation comprise discrete, subparallel strands to the north and south, but coalesce into a single broad shear zone in the central part of the area. For purposes of discussion, therefore, the RCSZ can be considered in terms of three distinct geographic and structural segments that are referred to herein as the southern, central, and northern segments, respectively (Figure 3).

The southern segment lies between the National Zoological Park (referred to hereafter as the "Zoo"; Figure 3) and the Potomac River Valley. It consists of two major strands, of which only the western strand is exposed south of the Zoo. The southernmost exposures of this strand are near the mouth of Rock Creek, where a very narrow (50-100 m) zone of strongly sheared rocks separating the Sykesville and Laurel Formations appears from beneath the alluvium in the Potomac River Valley. From there, this strand follows the east side of Rock Creek Valley to the Zoo. The walls of the shear zone along most of this segment are formed predominantly by the Laurel Formation on the east, and tonalites of the Georgetown Intrusive Suite and Kensington plutons to the west.

Near the southern edge of the Zoo, a second wider and more intensely deformed strand of mylonite emerges from beneath the Coastal Plain deposits along the east side of Rock Creek Valley (Figure 3). This "eastern" strand trends northwesterly at the Coastal Plain onlap and does not reappear from beneath the Coastal Plain farther to the south. At the Zoo, the two strands are separated by a narrow horse of unsheared and weakly sheared rocks. The intervening rocks are severely faulted, however, and constitute a series of large blocks within a tectonic mélange between the two strands.

The central segment of the RCSZ trends almost due north from the Zoo for about 8 km to a point where the shear zone crosses and leaves the valley of Rock Creek near the D.C.-Maryland line. The central segment contains the gradual coalescing of the two aforementioned strands, and thus constitutes the core of the shear zone. Consequently, the zone of severely sheared rocks is widest along this segment, approaching 2 km in the interval between the Zoo and Broad Branch.

Much of the central segment, as well as the immediately adjoining part of the southern segment, is characterized by abundant fault zones that represent at least three periods of motion. The complex deformation has resulted in juxtaposition of several different rock types on a very localized (outcrop) scale, a relation recognized by some earlier workers, who referred to this area in such terms as "the zone of mixed rocks" (Bassler, 1940; Fellows, 1950). This zone is, in fact, a tectonic mélange that lies along the junction of the two strands of the shear zone. The tectonic mélange is characterized by small blocks of variably sheared hornblende tonalite, amphibolite, serpentinite, chloritic schist, gabbro, and leucocratic granitoids of uncertain affinity, all of which are set in a "matrix" of weakly sheared to ultramylonitic Laurel Formation. Individual rock bodies are seldom traceable for distances greater than a few tens of meters within the tectonic mélange, and many are visibly bounded by faults and(or) bands of ultramylonite. All the known ultramafic and gabbroic bodies along the shear zone occur within the tectonic mélange, and the Laurel Formation exhibits abrupt changes in the degree of mylonitization along some fault zones. The walls of the shear zone along all of this segment are ultimately composed of the Laurel Formation to the east and Kensington Tonalite on the west.

The northern segment includes all of the RCSZ north of where it leaves Rock Creek Valley near the D.C.-Maryland line. This segment is less sharply demarcated as a single shear zone, and instead appears to splay into an irregular, anastomosing zone of ductile deformation localized in several bodies of Kensington Tonalite and in the closely foliated Loch Raven Schist farther to the north. Widely scattered outcrops of strongly sheared rocks occur across a zone as wide as 3 km, and are interspersed with outcrops of unsheared or weakly sheared rocks. Thus, the RCSZ appears to splay into several strands as it passes to the north. Unfortunately, a combination of sparse exposures, thick saprolite development, dense urbanization, closely foliated host rocks, and weaker geophysical expression cause the RCSZ to become increasingly difficult to trace beyond Rock Creek Valley.

Consequently, its full extent to the north, and the relationship between seemingly different strands of sheared rocks in that area, are not presently known. Most of the structural observations presented in this paper are, therefore, derived from the excellent exposures along the southern and central segments.

The RCSZ generally has a strong aeromagnetic expression (Figure 4) that helps delineate its continuity in areas of poor exposure. The geophysical expression is greatest along the central and southern segments, which are marked by an intense aeromagnetic gradient created by the sheared boundary between the strongly magnetic Laurel-Loch Raven rocks to the east and the weakly magnetic tonalites to the west. This gradient is less pronounced along the northern segment, but the aeromagnetic pattern in that area seems to support the interpretation that the RCSZ splays into multiple strands. A prominent curvilinear aeromagnetic anomaly beneath the Coastal Plain in downtown Washington may represent the southward continuation of the large eastern strand of the shear zone that disappears beneath the Coastal Plain at the south edge of the Zoo. This anomaly continues for another 15-20 km below the Coastal Plain in Virginia, and is aligned with a poorly exposed shear zone along the extreme eastern edge of the Piedmont in the Occoquon and Fort Belvoir quadrangles (Figure 1; Seiders and Mixon, 1981). The Virginia shear zone is reported to have kinematic characteristics similar to those of the RCSZ (Heimgartner, 1995).

NATURE AND INTENSITY OF DEFORMATION

The dominant characteristic of the shear zone is the pervasive, composite, mylonitic fabric produced by successive reuse and reactivation of older foliations. Reactivation is produced when an antithetic sense of shear operates along a preexisting foliation, whereas reuse occurs when shearing operates in a synthetic sense along preexisting foliations (Bell, 1986).

The expression of the ductile deformation is in large part controlled by the character of the different host rocks, being generally less regular in both intensity and distribution in the intrusive rocks than in metasedimentary units. The wide zone of ductile deformation that characterizes the central segment appears to result from the intersection of two large strands of the shear zone and the superposition of different episodes of deformation within relatively poorly resistant rocks of the Laurel Formation. There, the intensity of deformation appears to increase systematically from east to west, and abruptly culminates in a ductile fault zone localized along the contact between the Laurel Formation on the east, and Kensington Tonalite and other intrusive rocks to the west. This progression is consistently recognizable in most parts of the central segment, resulting in three general subzones corresponding to differing intensities of ductile deformation (Figure 5):

1) Protomylonite: weakly to moderately mylonitized, medium- and coarse-grained rocks characterized by a pervasive transposition foliation and locally cut by widely-spaced zones of more severely sheared rock with well-developed S-C fabrics. Older structures are easily recognizable in most of these rocks.

2) Mylonite: moderately to strongly phyllonitized and mylonitized, fine- and medium-grained rocks containing narrow layers of intensely sheared and crenulated rock as well as irregular zones of less sheared rock. Older structures are difficult to recognize in most of these rocks, which typically exhibit strong S-C fabrics and grain-size reduction.

3) Ultramylonite: severely sheared rocks composed of dense, massive to crenulated, very fine-grained mylonite that commonly resembles dark, fine-grained quartzite. Some of these rocks are unrecovered, quartz-ribbon mylonites. Except for a few small enclaves of less sheared rock, older structures are completely obliterated and recognition of original rock types is problematic because of the extreme grain-size reduction.

The progressive ductile deformation is particularly well displayed where the shear zone cuts olistolith-rich rocks of the Laurel Formation (Figure 6). The shear zone is more irregular, however, where it cuts the mafic tonalites of

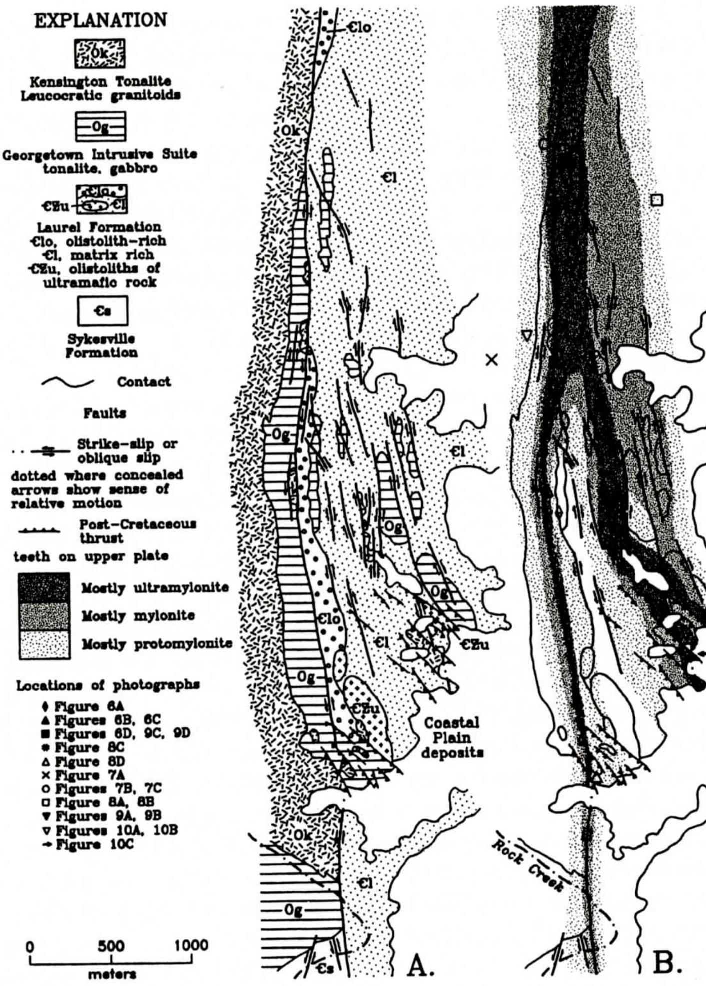

Figure 5. A) Geological map showing selected faults and rock units in parts of the southern and central segments of the Rock Creek shear zone. Arrows on faults indicate sense of motion and are not representative of the entire movement history of a particular fault. Paleozoic and post-Cretaceous faults, and small rock units within tectonic mélange are much more numerous than could be shown at scale of figure; B) map showing intensity of ductile deformation in same area as (A). Locations of photographs shown in figures 6-10 are designated by symbols, which are identified in map explanation.

the Georgetown Intrusive Suite and some of the mafic and ultramafic blocks in the tectonic mélange near the Zoo. In fact, most of the mafic tonalite bodies affected by the shear zone characteristically exhibit only moderately pronounced S-C fabrics that may be locally accompanied by narrow shear bands along which the rock has been retrograded to chlorite-actinolite-epidote-oligoclase-quartz ultramylonite (mineral assemblages are listed in order of increasing relative abundance). Well-developed mylonite typified by severe grain-size reduction occurs only along narrow zones in the larger bodies, but is somewhat more common in the smaller tonalite blocks within the tectonic mélange.

Of the intrusive rocks, the Kensington Tonalite exhibits the most pervasive ductile fabric (Figure 7). Most of the eastern half of the large southern pluton is protomylonite with multiple,

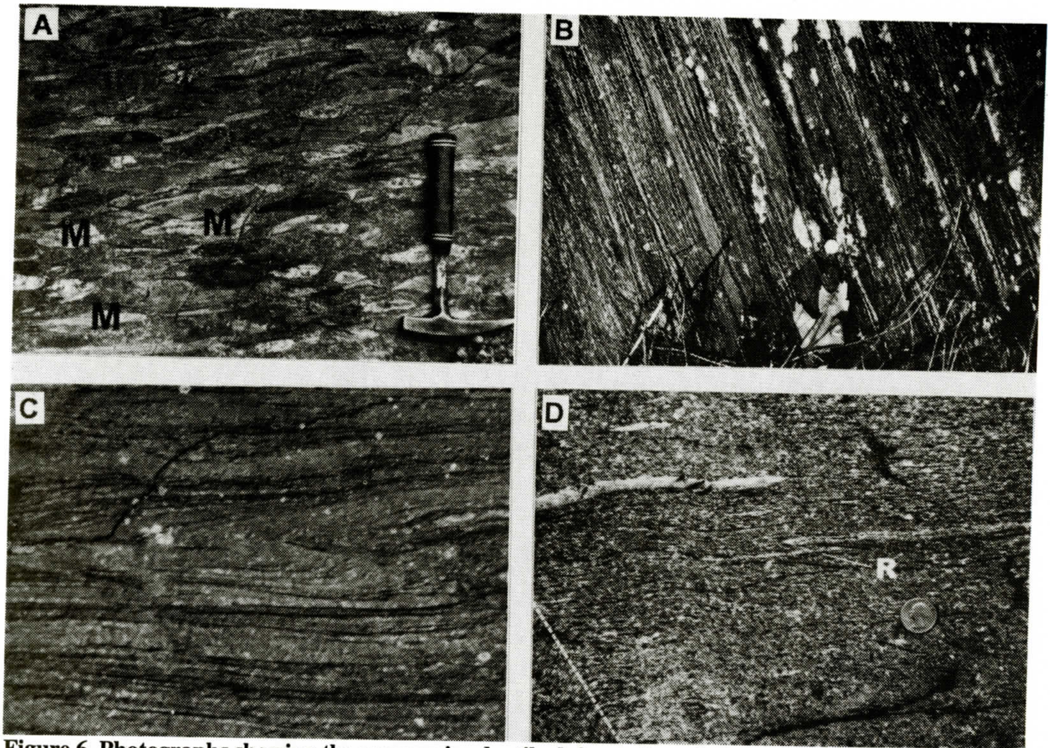

Figure 6. Photographs showing the progressive ductile deformation of olistolith-rich unit in the Laurel Formation. Faces are oriented perpendicular to mylonitic foliation and subparallel to latest, northwest-plunging mineral elongation lineation. Refer to figure 5B for locations. A) olistolith-rich slide unit, matrix very weakly mylonitized, situated in horse between two shear zone strands. Note tails on some metaarenite clasts (M) giving sinistral sense of shear. Hammer is 31 cm long. B) same rock unit, 200 m north of (A), strongly mylonitized, light-colored layers are flattened metaarenite clasts, dark lines are flattened Loch Raven Schist. Coin is 1.8 cm in diameter. C) mylonite 10 m west of (B), with complexly folded metaarenite (porphyro)clast in center showing asymmetric tails that may have initially been formed during sinistral shear and were dragged back under the center of clast during subsequent dextral shearing. Coin is 1.8 cm in diameter. D) 500 m north of (C), ultramylonite with mesoscopic quartz ribbons (R) and late oblique dextral shear band (dashed line). Tails of ribbon above coin are similar to those shown in "C" and are suggestive of two episodes of antithetic shearing. Coin is 2.5 cm in diameter.

subparallel foliations and few relict igneous features. Quartz and feldspar are typically strung out into granulated lenses set off by closely spaced, crossing shear band foliations defined by muscovite and biotite (±chlorite). It becomes progressively more sheared toward the contact with the Laurel Formation, where it is a dense ultramylonite that resembles fine-grained feldspathic quartzite. A distinctive feature in the northern part of this pluton are widely scattered, box-shaped porphyroblasts of microcline (Figure 7) that locally enclose and replace protomylonitic tonalite. These are also porphyroclasts, because they are themselves aligned within and locally deformed by a younger mylonitic foliation. The microcline appears to occur only in the Kensington and is not evident in any adjacent rock units.

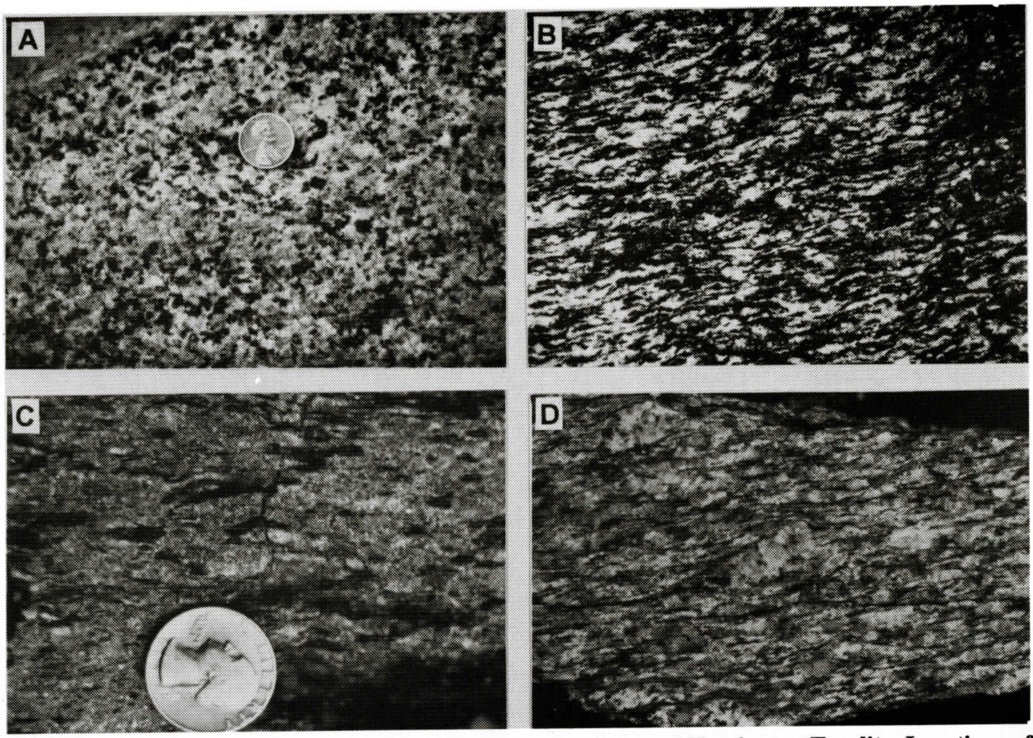

Figure 7. Photographs showing progressive ductile deformation of Kensington Tonalite. Locations of A-C are shown in figure 5B. A) Unsheared, weakly foliated tonalite from center of pluton. Coin is 1.8 cm wide. B) Protomylonitic tonalite, showing multiple foliations and incipient segregation into biotitic and quartzo-feldspathic layers. Field of view is approximately 10 cm wide. C) Quartzo-feldspathic ultramylonite with a few quartz and biotite porphyroclasts. Coin is 2.5 cm in diameter. D) Sawed face showing relationship of fabric elements and microcline porphyroblasts. Width of face is about 9 cm. Porphyroblasts grow within and deform older S-surfaces (inclined to left), which in turn deforms relict compositional layering defined by quartzo-feldspathic and biotitic bands (gently inclined to right). All of these and the porphyroblasts are deformed by younger dextral shear band foliation (C-surfaces), which is moderately inclined to the left and has created noticeable tails of finely granulated quartz, feldspars, and mica on the microcline. Face is cut perpendicular to foliation and parallel to latest mineral elongation. Location of sample is shown in figure 3.

DEFORMATION HISTORY

Despite the strongly composite aspect of the shear zone, structures resulting from several distinct types of deformation are recognizable at many places. In apparent order of decreasing age, these include: 1) Mylonitic foliation, shear bands, microfolds, and related features exhibiting sinistral-slip kinematics and produced under prograde, lower to middle amphibolite facies conditions; 2) Ductile, oblique- and strike-slip faults with sinistral kinematics; 3) Moderate to intense phyllonitic to ultramylonitic foliation, microfolds, and late oblique shear bands exhibiting a strong dextral shear sense and generated under retrograde, greenschist to subgreenschist facies conditions; 4) Ductile to semibrittle, dextral- and oblique-slip fault zones that cut all of the above features; and 5) Brittle, northeast-directed, high-angle thrust faulting that has affected Coastal Plain deposits as well as the crystalline rocks.

Structures Produced By Sinistral Shear

The composite mylonitic foliation in the RCSZ contains evidence for two principal episodes of antithetic motion: an earlier predominantly

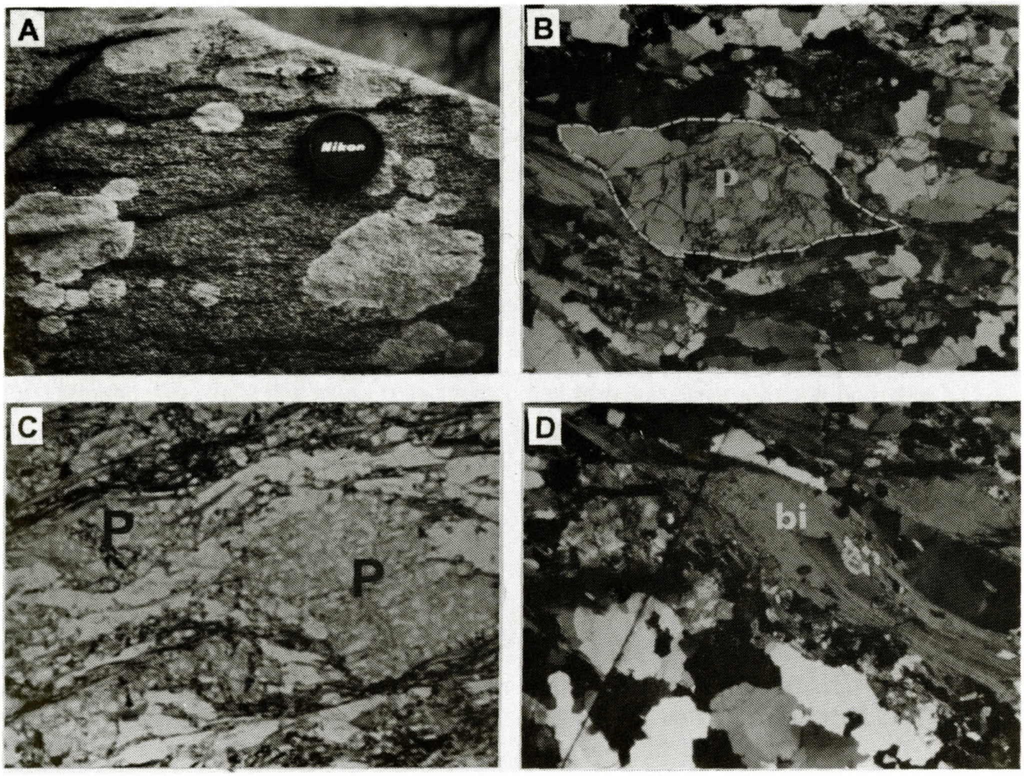

Figure 8. Relict features resulting from sinistral shear preserved in Laurel Formation along east wall of RCSZ and in tonalite blocks. Locations are shown in figure 5B. A) outcrop face, oriented sub-parallel to southwest-plunging stretching lineation, showing weak sinistral shear band foliation (slightly inclined to left) transposing and reusing Sligo Creek foliation (inclined to right). Note asymmetric tails on quartz clast above lens cap, which is 5 cm in diameter; B) photomicrograph from nearby outcrop showing characteristic coarse protomylonitic foliation and asymmetric porphyroclast (P). Field of view is 5 mm. Crossed nicols. C) ultramylonitic hornblende tonalite of the Georgetown Intrusive Suite, showing relict asymmetric plagioclase porphyroclasts (P) giving sinistral sense of shear. Field of view is 5 mm. Crossed nicols. D) Protomylonitic Kensington Tonalite west of shear zone. Most structures in this rock result from late dextral shearing; however, asymmetry of relict biotite porphyroclast (bi) suggests sinistral shear. Field of view is 5 mm. Crossed nicols.

sinistral episode and a later dextral one. The shear zone is dominated by pervasive retrograde mineral assemblages and associated kinematic indicators produced during the latter episode, which have severely overprinted older structures and thus obscured much of the direct evidence for earlier events. Complex structures (e.g., refolded microfolds, porphyroclasts that appear to have had their earlier tails dragged back under their cores) from which an earlier episode of shearing could be inferred are relatively common; however, structures giving an unambiguous sense of sinistral displacement associated with prograde amphibolite facies metamorphism are largely relict features, being visible mainly along the eastern walls of the shear zone and in isolated enclaves of rock elsewhere that have resisted subsequent ductile deformation and retrograde metamorphism (Figure 8). An important characteristic is that the rocks in which these relict structures are best expressed are virtually all medium- and coarse-grained.

The most widespread evidence for sinistral shearing is found within the Laurel Formation along the eastern wall in the central and northern segments, where many outcrops exhibit a widely spaced ductile structure termed transposition foliation by Fleming and others (1994). This fabric trends north-south and cuts obliquely across and locally transposes and reuses the more northeasterly trending foliation characteristic of the Laurel Formation. As the shear zone is approached, the transposition foliation and grain-size reduction become much more pervasive; the increasingly mylonitic appearance of the rock matrix is accompanied by an increasing number of shear bands and asymmetric clasts, some of which exhibit a sinistral sense of shear. Microstructures from these rocks reveal a similar kinematic sense. These structures are commonly associated with moderate to steep, southwest-plunging lineations produced by elongated quartz rods and clasts, microfolds, and foliation intersections; they appear to be spatially and geometrically related to Silver Spring and Sligo Creek folds. The map pattern in this area provides further evidence for sinistral shear. The angle of intersection of the southwesterly-trending folds and megascopic compositional layering in the Loch Raven-Laurel motif with the northward-trending shear zone, and their apparent sense of rotation into the zone, indicate a sinistral sense of shear.

The rocks in which these structures formed were undergoing at least lower to middle amphibolite facies metamorphism, with the actual presence or absence of index minerals at any particular place being a function of bulk composition. Garnets are widely scattered in the somewhat sandy matrix of the Laurel, which typically consists of the assemblage (garnet-)biotite-oligoclase-muscovite-quartz; but they are ubiquitous within micaceous olistoliths. Some of the more olistolith-rich rocks were evidently sufficiently aluminous to allow staurolite to form as well (Figure 9). The garnet and staurolite have grown across the mylonitic foliation but do not appear to have been rotated or otherwise deformed during the sinistral shearing. Garnet and staurolite are also common constituents in the Laurel east of the shear zone, where they grow within the northeast-to-southwest trending foliation that parallels Sligo Creek folds. These relations indicate that the sinistral shearing accompanied, and was outlasted by, staurolite-grade metamorphism. All of the above features in this part of the shear zone are locally deformed by small, widely spaced dextral shear bands along which the rock is retrograded to muscovite-chlorite (±biotite)-epidote-albite-quartz phyllonite.

Sparse evidence for sinistral shearing can be seen elsewhere in the shear zone (Figure 8), chiefly in blocks of more resistant mafic tonalite of the Georgetown Intrusive Suite, in the horse of weakly sheared Laurel Formation that separates the two major strands of the RCSZ south of the Zoo, and more rarely in the large pluton of Kensington Tonalite that bounds the west side of the central segment. Although most of the mafic tonalitic rocks are retrograded to chlorite-actinolite-epidote-albite-quartz mylonites and phyllonites, relict enclaves that have resisted the subsequent dextral shearing do exist in most of these tectonic blocks. These enclaves are characterized by porphyroclasts or small aggregates of coarse hornblende and andesine within a severely sheared, fine-grained matrix. Where not refolded, some of the porphyroclasts exhibit relict tails whose asymmetry is clearly sinistral.

Sinistral-Slip Ductile Faults

A system of ductile strike-slip and oblique-slip faults is exposed at several localities along the RCSZ (Figure 5), concentrated mainly along the contact between the Laurel Formation and Kensington Tonalite, and to a lesser degree, along the eastern part of the tectonic mélange, just north of the Zoo. Offset of adjacent units, ductile drag of mylonitic layering, and rare asymmetric folds of distinctive markers (e.g., dikes) observed at a few fault exposures indicate a dominantly sinistral motion, with the east side also having been upthrown on some fault planes. Observed fault planes generally dip moderately to steeply west and trend northwest. The original orientation of these faults is not known because the parts of the shear zone in which they are known to occur have been severely overprinted and locally reactivated by subsequent antithetic deformation; consequently most of the faults probably were subsequently rotated or reactivated.

Because of the lack of clear marker units and subsequent antithetic shearing and faulting, the amount of displacement along the ductile fault zone cannot be reliably determined, but the map pattern (Figure 3) exhibits a striking truncation of folds and rock units along the eastern wall of the shear zone that suggests regional-scale sinistral dislocation. The Loch Raven Formation and the upper, olistolith-rich unit of the Laurel appear to be completely removed by shearing, for example; these units and axes of the southwest-plunging Silver Spring and Sligo Creek folds exhibit large-scale sinistral rotation into parallelism with the shear zone. The probable equivalence of 1) the sliver of olistolith-rich Laurel Formation that lies between the two strands of the shear zone near the Zoo (Figure 5) with the main mass of the same unit that lies within the Silver Spring syncline east of the northern segment (Figure 3), and 2) the small tonalite blocks within the tectonic mélange near the Zoo with the main Georgetown pluton west of shear zone to the south (Figure 5), indicate at least several km of sinistral displacement.

Structures Produced By Dextral Shear

Structures and retrograde mineral assemblages generated by shearing during greenschist facies metamorphism are ubiquitous at most places in the RCSZ. All these features exhibit strong dextral kinematics and have commonly reactivated, reoriented, and(or) completely overprinted the older mylonitic foliation(s), resulting in a strongly composite fabric. This group of structures is pervasive throughout the shear zone, but is especially dominant within the central segment, where they occupy a wide core of ultramylonite.

Structures generated by dextral shearing range from widely spaced shear bands along the far eastern walls of the shear zone, to unrecovered quartz-ribbon ultramylonites in the core of the shear zone. The sense of dextral asymmetry seen in many porphyroclasts within the shear zone reflect this event (Figure 9), as do a majority of shear bands and numerous steeply northwest-plunging mesoscopic and microscopic folds, mineral elongations, and intersection lineations.

The reactivation of earlier mylonitic foliation and deformation of earlier microfolds and asymmetric structures has produced a variety of relatively complex fabrics that are often ambiguous or difficult to interpret. Due to the severity of the dextral shearing, the original forms of porphyroclasts generated during the earlier sinistral shearing are rarely preserved; some of the larger and more competent types appear to have had their tails dragged back under their cores, similar to those reported from antithetically reactivated shear zones elsewhere (e.g., Costa and Gates, 1992.) In others, the antithetic tails were simply rotated parallel to new synthetic tails, producing double-tailed porphyroclasts. Quartz ribbons showing limited or no recovery are particularly common where ultramylonite bands deform olistolith-rich zones of the Laurel. This relation suggests that the ribbons are derived chiefly from stretching of quartz and metaarenite clasts or earlier porphyroclasts derived therefrom (as opposed to recrystallization), a conclusion supported by mesoscopic evidence (e.g., Figure 6). Numerous subgrains within many quartz ribbons are consistently oriented with their long axes (flattening planes) at an oblique angle to the ribbons themselves. The acute angle thus formed with the macroscopic foliation indicates dextral shear.

The latest ductile feature evident in the RCSZ is a widely spaced, oblique shear-band foliation. The shear bands typically intersect the mylonitic foliation at about 35 degrees and occur in the most homogeneous, finest-grained rocks, such as quartz-ribbon ultramylonites. Conjugate sets were rarely observed, with the majority of late shear bands occurring as a single, northeast-trending set. Their intersection with the shear zone walls and with the earlier, composite mylonitic foliation indicates a dextral shear sense. Similar features have been widely described from shear zones elsewhere (e.g., Sibson, 1977; Bell, 1978; Platt, 1979; Berthe and others, 1979) and are thought to represent strain hardening during the final phase of ductile deformation in a shear zone as the tem-

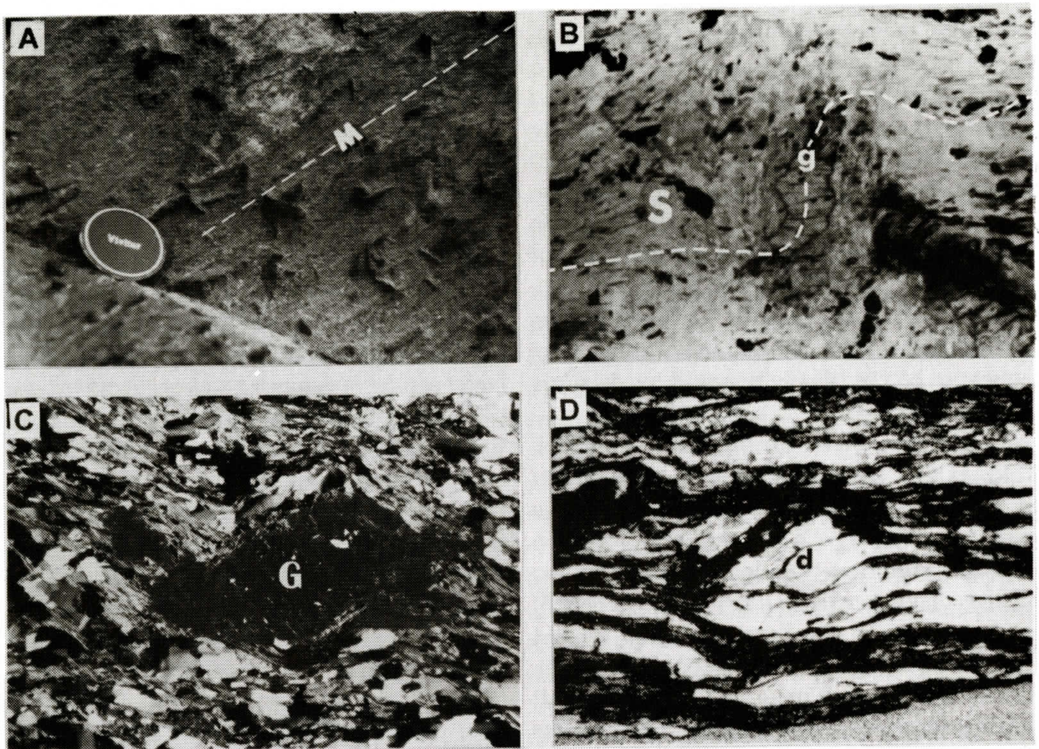

Figure 9. Relations of prograde and retrograde minerals to dextral shear. A) Coarse staurolite pseudomorphs growing across coarse mylonitic foliation (M) in Laurel Formation. B) photomicrograph from same locality showing strong dextral rotation (dashed line) of staurolite (S), which has been retrograded to sericite and has a small, mostly chloritized garnet core (g). Location is shown on figure 5B. Field of view is 5 mm. Plane polarized light. C) Photomicrograph showing rotated, mostly chloritized garnet porphyroclast (G) in quartz ribbon ultramylonite. Same location as figure 6D. Tails indicate dextral shear. Field of view is 5 mm. Crossed nicols. D) photomicrograph from same location as (C), showing folding of quartz ribbons. Some ribbons, such as (d), show a clear sense of dextral shear. Field of view is 5 mm. Crossed nicols.

perature falls (White and others, 1980). This hypothesis is supported by the occurrence of these structures in areas of the RCSZ where semibrittle dextral strike-slip faults (see below) are also abundant.

The dextral shearing was accompanied by lower to middle greenschist facies metamorphism. Common assemblages include muscovite-biotite (or chlorite)-epidote-oligoclase-quartz in metasedimentary rocks, chlorite-actinolite-epidote-oligoclase-quartz in mafic tonalites, and muscovite-biotite (or chlorite)-microcline-oligoclase-quartz in Kensington Tonalite. Plagioclase is extensively sausseritized at many places. Biotite appears to be metastable in the rocks least affected by dextral shearing, mainly along the outer walls of the RCSZ, but it has been altered to chlorite within widely spaced dextral shear bands that cut these rocks. Chlorite is the stable phase throughout the mylonitic and ultramylonitic rocks in the middle of the shear zone (Figure 9), suggesting that the shearing was accompanied, and probably facilitated, by abundant water. Garnets formed during earlier events in the Laurel Formation were commonly rotated and most were partially to wholly chloritized. Staurolite was thoroughly retrograded to shimmer aggregates of fine sericite, and some of the aggregates have asymmetric tails. The retrograding of amphibolite-facies minerals was most complete within the core of the shear zone, although this effect is also evident at great distances from the zone. Numerous other investigators have noted the pervasive retrogressive metamorphism throughout this part of the Piedmont (e.g., Fisher, 1963; Hopson, 1964).

Dextral Faults

Numerous dextral-slip faults are exposed in the central segment of the shear zone between Broad Branch and the Zoo (Figures 3 and 5), and less commonly in the adjoining part of the southern segment. They are particularly abundant in the tectonic mélange where the two strands coalesce, and within zones of ultramylonite. Many of these fault planes also exhibit a significant component of vertical displacement, with the west side invariably being upthrown. Mullions, grooves, and slickenlines are abundant; some plunge as steeply as 60 degrees, although most are much less steeply inclined. Tight to open, steeply northwest-plunging folds of the mylonitic layering commonly occur adjacent to individual faults; at some places, ductile structures are sharply bent or the host rock is broken into coarse fragments and locally injected by quartz veins. These characteristics indicate that the rocks were behaving largely in a brittle or semibrittle fashion during this episode.

Many of the dextral faults visibly bound tectonic blocks within the mélange. However, some of these fault planes appear to have reactivated segments of the older, ductile fault zone along the Laurel-Kensington contact. This is directly shown in a few places by the dextral offset or rotation of sinistral fault zones, which do not exhibit any brittle structures, by faults showing minor brecciation.

It is not known whether the dextral fault system extends beyond the central segment of the shear zone. No such faults have been observed to the north, but some fault planes appear to extend southward beneath the Coastal Plain overlap at the Zoo. This episode of faulting appears to have mainly manifested itself at the junction of the two southern strands of the shear zone, where it has played a major role in generating the tectonic mélange and in rotating older structures in the wide central segment. The marked bend of rock units to the southeast at this junction coincides with the most abundant of these faults, and may result in part from this episode. It seems plausible that the faulting represents a more brittle continuation of the dextral shearing, resulting from a continuation of high strain while the rocks cooled through the ductile-brittle transition.

Post-Cretaceous Thrust Faults

A much younger system of thrust faults that cut all of the older bedrock structures as well as Coastal Plain deposits has long been recognized in the lower valley of Rock Creek and nearby areas (Bassler, 1940; Darton, 1950; 1951; Fleming and others, 1994). All known faults of this type are localized in swarms in and near the central and southern segments of the RCSZ, where they have reactivated segments of some Paleozoic faults and displaced sediments at least as young as middle Pleistocene (Figure 10). Nearly all strike northwest and dip from less than 10 degrees to as much as 75 degrees southwest. Such faults are visible in many outcrops in this part of the valley, and have been reported from numerous, mostly temporary exposures in subway tunnels, building excavations, and from boreholes (e.g., Darton, 1950; O'Connor, 1982; 1989; Prowell, 1983). An excellent example of a fault cutting Coastal Plain deposits is preserved in a small enclosure at the Adams Mill Road entrance to the Zoo, where mylonitized Laurel Formation is thrust over gravel of the lower Cretaceous Potomac Group (Figure 10C).

Most of the post-Cretaceous faults appear to have relatively small throw, generally a few meters or less, based on observed offset of units across fault planes. Some fault planes are marked by gouge or breccia that is typically only a few cm thick but rarely approaches one meter. Grooves and plow marks are common, especially where small breccia fragments of hard, quartzose ultramylonite were caught and dragged in the fault plane. In some locations, the post-Cretaceous faults appear to have reactivated segments of Paleozoic oblique-slip

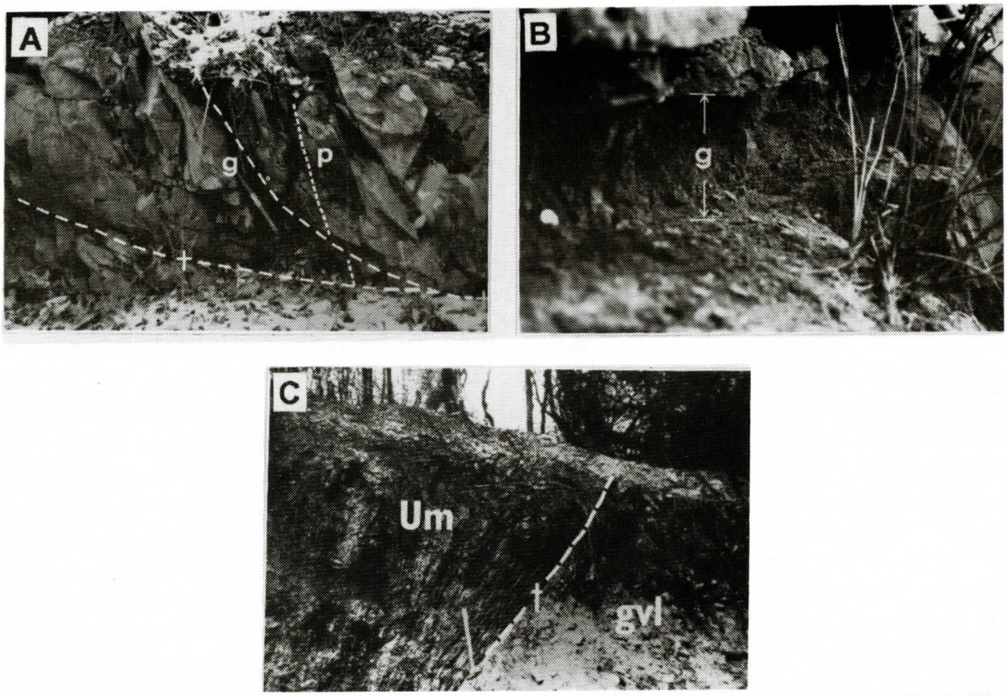

Figure 10. Field relations of post-Cretaceous thrust faults. Locations are shown in figure 5B. A) Photograph showing relation between gently inclined post-Cretaceous thrust faults (t, long dashes) and steeply inclined Paleozoic fault zone (P). The post-Cretaceous fault appears to splay into at least two planes, the upper of which has reactivated and formed a narrow zone of fault gouge (g) where it follows the steeply dipping Paleozoic fault zone. Hammer is 30 cm long. Country rock is mylonitic hornblende tonalite of the Georgetown Intrusive Suite, Taft Quarry, southern Rock Creek Park; B) Zone of fault gouge (g) approximately 0.4 m thick developed along gently inclined thrust in tonalite. Same location as (A); C) ultramylonite (Um) overlying poorly consolidated Tertiary gravel (gvl) along thrust. Photo by N.H. Darton (1950) from road cut along Adams Mill Road.

faults, which presumably represented zones of weakness when the Cenozoic thrusting was initiated. Where both sets of faults occur together, such as in the tectonic mélange near the Zoo, the younger thrusts commonly follow the earlier fault planes for various distances. Splays are also very common. The imposition of these latest fault motions on already polydeformed rocks makes it difficult to interpret the older structures in the affected rocks and to relate patterns of older ductile deformation to other parts of the shear zone not affected by late thrusting.

AGE OF DEFORMATION

The contrasting structural elements that constitute the RCSZ record an episodic history of deformation that potentially spans the entire period of geologic time since the Early Ordovician. An exact age for each individual episode of deformation is difficult to specify, partly because the ages of many of the affected rocks are poorly constrained, but also because at least some of the events themselves may have taken place over extended periods. Thus, it should be emphasized that the chronological history postulated below for the RCSZ is somewhat speculative, and that there may be other equally valid age interpretations for the various periods of deformation.

The age of the ductile deformation in the RCSZ depends on the ages of affected rocks, particularly the Kensington Tonalite, and the relationship to major fold phases, metamorphic conditions, and other characteristics that help to constrain Paleozoic tectonic history in this region of the Piedmont. Sinistral shearing is the earliest ductile event clearly recorded by structures in the RCSZ. The ductile fault zone within the core of the RCSZ, which separates the Georgetown Intrusive Suite and Kensington Tonalite from the Laurel Formation, and which also exhibits net sinistral displacement, is very probably associated with the sinistral shearing and may represent the culmination of the same event. This event clearly initiated after crystallization of the Georgetown Intrusive Suite (465±3 Ma) and Kensington Tonalite (460±4 Ma) because these rocks were deformed by the sinistral shearing. It can therefore be no older than Early Ordovician.

Evidence for a minimum age for the sinistral shearing and faulting is less conclusive, but several characteristics indirectly suggest that the event may have occurred not long after the Kensington Tonalite began to crystallize. In the northern segment of the shear zone, the Kensington contains distinctive, somewhat box-shaped porphyroblasts of microcline (Figure 7). The porphyroblasts have largely replaced severely granulated plagioclase and quartz, and appear to have grown across and replaced an earlier protomylonitic foliation (Hopson's, 1964, p. 167 "protoclastic" deformation). The microcline has not been observed in any other rock units near the RCSZ, nor does it appear to have been rotated as it grew. The tonalite in which the microcline occurs, however, typically exhibits a pervasive, late mylonitic foliation with dextral kinematics, and some of the microcline crystals show the effects of the dextral shearing in the form of asymmetric tails and pressure shadows, displaced microfractures, and localized marginal crushing and alteration to sericite and quartz. The growth of the microcline thus appears to bracket the two antithetic episodes of shearing, forming porphyroblasts with respect to the earlier, sinistral event, and porphyroclasts with respect to the later, dextral event.

The habit of the microcline crystals suggests a metasomatic origin, with at least two possibilities for the source of potassium. One possibility is that the potassium was emplaced during shearing from fluids external to the tonalite circulating at depth within the fault zone. A second alternative is that the potassium was derived directly from the tonalite, either from residual potassic fluids permeating the rock following the shearing, or perhaps emanating from less crystallized parts of the pluton at depth. The lack of microcline or other textural evidence for potassium enrichment in adjacent rocks, such as the Georgetown Intrusive Suite and Laurel Formation, tends to support the second possibility. Similarly, the presence of modal microcline in some samples of unsheared tonalite (Fleming and others, 1994) suggests that at least part of the potassium is an original constituent of the Kensington magma. The markedly elongated shape and generally protomylonitic texture of the Kensington plutons, and the fact that they are concentrated along the RCSZ, also support the notion that the tonalite was intruded into a zone of high strain, i.e., perhaps just prior to or during the inception of shearing. It is interesting to note that Hopson (1964), who made extensive petrographic analyses of the Kensington, reached much the same conclusion. If the above lines of reasoning are correct, the sinistral shearing and ductile faulting along the RCSZ were associated with a tectonic and intrusive event that took place during the Early to Middle Ordovician, and would thus correspond to the Taconic orogen (Drake and others, 1989).

Regional metamorphic evidence also implies an Ordovician age for the sinistral deformation. Assemblages produced during an initial, middle to upper amphibolite facies metamorphism are widespread in the Loch Raven Formation and adjacent metasedimentary rocks in the Maryland Piedmont, where retrograded staurolite, kyanite, and fibrolitic sillimanite are common constituents (Crowley, 1976; Hopson, 1964). These minerals are genetically associated with north- to northeast-trending foliations and southwest- and northeast-plunging folds (Crowley, 1976; A.A. Drake, Jr., unpublished data) that appear to be continuous with, and thus equivalent to, the Sligo Creek folds and foliation that contain the garnet and staurolite adjacent to the RCSZ. At many places, the kyanite has grown across the foliation, indicating that the thermal peak of this event outlasted the penetrative deformation, a pattern similar to that observed in the relict sinistral structures in the RCSZ. It seems reasonable to speculate that the folding and prograde metamorphism observed in the Loch Raven-Laurel motif adjacent to the shear zone are the result of the same event that produced the similar features further to the northeast. In the latter area, the amphibolite facies rocks and attendant structures are cut by several relatively undeformed, presumably late- or post-kinematic granitoid plutons, as well as several undeformed pegmatite bodies, which are Late Ordovician (440-450 Ma; Hopson, 1964; A.K. Sinha, written communication, 1993). Consequently, this episode of folding and metamorphism has been widely interpreted to reflect Taconic deformation (Hopson, 1964; Fisher, 1979; Muth and others, 1979; Muller and Chapin, 1984). If the structural and metamorphic equivalence postulated above is correct, then the tectonic event that produced the prograde mineral assemblages and Sligo Creek structures must have occurred during the Early to Middle Ordovician, and is thus also related to the Taconic orogen (Drake and others, 1989).

The ages of the dextral shearing and faulting that affected the RCSZ cannot be directly determined, but evidence of an indirect and largely regional nature provides a basis for limited speculation. The dextral event was characterized by extremely high strain and low temperature, indicated by the development of a broad zone containing numerous quartz ribbons, well-developed late oblique shear-band foliation, and low-rank mineral assemblages. Many faults within this zone contain structures indicative of formation at or near the ductile-brittle transition; i.e., near the lower end of greenschist-facies conditions. A genetic relation between the dextral shearing and the faults seems likely based on their close geographic association within the RCSZ as well as their similar kinematics. A reasonable assumption is that the faults represent a somewhat overlapping, but generally younger phase of deformation as the rocks cooled below the transition and the shear zone strain hardened during the waning stages of the dextral event.

The key feature of this event in terms of its regional affiliation is that it appears to have taken place entirely under greenschist facies (or lesser) conditions, producing pervasive retrograde mineral assemblages. Secondly, the foliations, microfolds, shear bands, and other features associated with the dextral shearing are the latest penetrative structures evident in these rocks. Numerous workers have noted a similar pattern of widespread, late retrograde assemblages and associated penetrative structures in a variety of rocks throughout the Baltimore-Washington area (Fisher, 1963, 1970; Reed and Jolly, 1963; Hopson, 1964; Crowley, 1976; Drake, 1985b, 1989). Many published mineral ages from this part of the Piedmont, especially K-Ar mica ages, cluster between 330 and 300 Ma (Davis and others, 1960; Lapham and Bassett, 1964; Hopson, 1964; Wetherill and others, 1966), and recent determinations from muscovite in the Loch Raven and Laurel Formations indicate a similar age (A.A. Drake, Jr., unpublished data). Similarly, U-Pb isotopic studies on zircons from the Gunpowder granite gneiss (Hopson, 1964) northeast of Baltimore suggest an emplacement age of about 330 Ma (Grauert, 1973). These data generally point to a significant Alleghanian tectonothermal event, as well as a late Paleozoic time of thermal closure below greenschist conditions for this part of the Piedmont.

There is no evidence to suggest that the overall thermal history of the RCSZ was significantly different from the regional pattern. It also seems reasonable to speculate that conditions never fell below greenschist facies in the D.C. Piedmont before the late Paleozoic; that is, the RCSZ probably remained buried at sufficient depth to maintain ductile conditions throughout most of the Paleozoic. The apparent timing of closure through the ductile-brittle transition, and thus the latest Paleozoic motions on the RCSZ, coincide with the Alleghanian orogen. Alleghanian deformation and plutonism are well known from the Piedmont in the Fredericksburg and Richmond, Virginia areas, about 75-150 km south of the RCSZ (Durrant and others, 1980; Glover and others, 1983; Wright and others, 1975; Pavlides and others, 1982; Sutter and others, 1985), and there is strong evidence for large-scale dextral shear along fault zones that cut "Alleghanian" or "300 m.y." granites of the eastern Piedmont (Hatcher and others, 1977; Sacks and others, 1991; Bobyarchick and Glover, 1979; Bobyarchick, 1981; 1988). Dextral shear zones described as "post-Taconic" have also been recognized in the northern Piedmont between Baltimore and Philadelphia (Valentino and others, 1992). In summary, although positive evidence for Alleghanian strike-slip deformation has not previously been reported from the D.C. area, its existence does not seem surprising given the regional setting. It should also be noted that the duration of the dextral shearing and faulting in the RCSZ is very poorly constrained. Given that this event produced a complex zone of ultramylonite and tectonic mélange, as well as an extensive series of both ductile and brittle structures, and in view of the comparatively long history postulated for the Alleghanian event in the southern Appalachians (Hatcher, 1989; Hatcher and others, 1989), the late Paleozoic structures evident within the RCSZ may represent an episodic history of deformation that took place over a prolonged period of time.

The latest deformation in the RCSZ is represented by the system of post-Cretaceous thrust faults. There is considerable evidence that this system has been active throughout the Cenozoic. Coastal Plain units occur at progressively greater elevations with increasing distance west of Rock Creek, and the differential uplift appears to affect older units more than younger ones (Fleming and others, 1992; 1994). This relation suggests that Coastal Plain sedimentation has been accompanied by episodic activity on the fault system during the Cenozoic. Because of this, it is impossible to assign a precise age to any particular fault or part of the fault system, or to reliably evaluate the potential for additional activity; hence, the entire system must simply be considered as "post-Cretaceous".

REGIONAL EXTENT AND TECTONIC SIGNIFICANCE

Structures in the RCSZ record at least two significant episodes of Paleozoic strike-slip deformation that occurred under considerably different regimes (Figure 11). The earlier episode is represented by relict amphibolite facies assemblages, relatively coarse mylonitic foliation, and various kinematic indicators that indicate sinistral motion. Textural evidence for sinistral shearing is preserved chiefly along the eastern wall of the shear zone and in isolated enclaves elsewhere that withstood complete reactivation by younger shearing and faulting. This episode is thought to be coincident with development of Silver Spring and Sligo Creek folds and related southwest-verging structures east of the shear zone, and to slightly post-date intrusion of 460 Ma Kensington Tonalite. Ductile faulting during this event is primarily responsible for the regional-scale structural discontinuities evident in the map pattern across the shear zone (Figure 3). This episode probably occurred during the Taconic.

A second major episode of shearing is indicated throughout most of the shear zone in the form of numerous bands of fine-grained ultramylonite, many with well-developed quartz ribbons; pervasive retrograde, mostly chlorite-zone mineral assemblages; and numerous small, northwest-plunging folds, late oblique shear bands, and other indicators of dextral movement. The dextral shearing reactivated older mylonitic foliations, resulting in complexly folded mylonitic layers at places and the ubiquitous composite ductile fabric that characterizes the shear zone. Direct evidence of earlier events, as well as the identity of some original rock types, is completely obscured at many places. This episode is probably coincident in time with the growth of Rock Creek folds east of the shear zone, and with similar, generally north-trending folds and late, west-facing shear band foliation (the "S4", "strain-slip cleavage", or "microshears" of Cloos, 1964, p. 238-240) to the west. A high strain rate appears to have been maintained as the rocks strain hardened during the ductile-brittle transition, resulting in a series of semi-brittle dextral- and oblique slip faults that generated a tectonic mélange at the junction of two major strands of the shear zone. These conditions are compatible with the Alleghanian event, when the rocks in this region

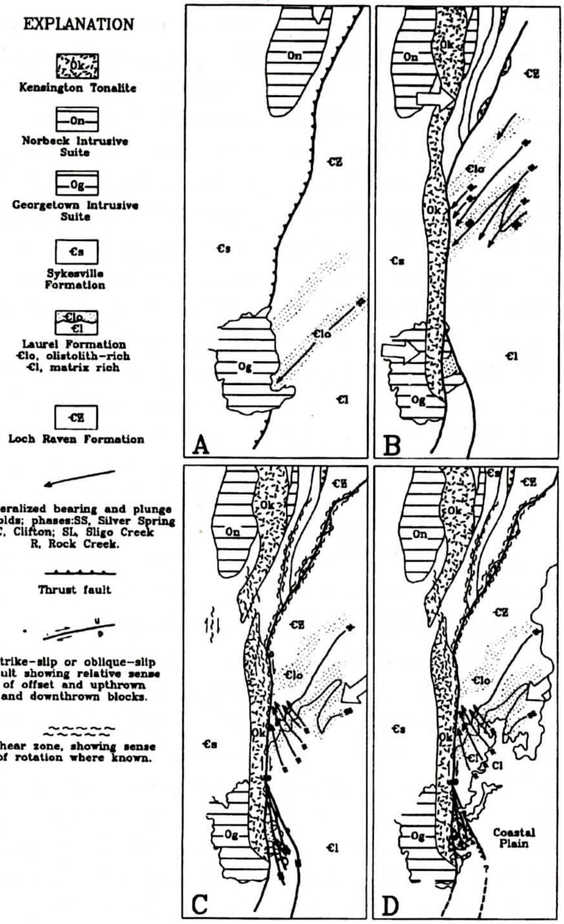

Figure 11. Schematic diagram showing evolution of major structural elements of RCSZ in relation to changing tectonic conditions. A) Development of stress continuum dominated by sinistral transpression produces Silver Spring syncline and intrusion of Georgetown and Norbeck Intrusive Suites at about 465 Ma. B) Development of Sligo Creek folds and dominant regional foliation in Laurel Formation marks continuing transpression. Emplacement of Kensington Tonalite at about 460 Ma and development of ductile conditions leads to sinistral shearing and faulting that overprints or reorients any earlier thrust-related structures that may have existed along the contact between the Sykesville and Laurel Formations. Taconic middle amphibolite facies (or higher) regional metamorphism appears to have outlasted the deformation. C) Initiation of dextral shearing and faulting during the late Paleozoic, culminating in tectonic mélange in lower Rock Creek Valley as shear zone cools below greenschist facies at approximately 300-330 Ma. D) Cenozoic thrust faulting initiated sometime after the Cretaceous, when compressive conditions were established along eastern North America.

underwent extensive dextral shearing, retrograde metamorphism, and thermal closure with respect to micas.

The ultimate location of the RCSZ is probably attributable to one or more large contrasts in bulk material properties. Such large-scale inhomogeneity could result from several possible conditions. One of these is likely to be represented by the contact between coarse-grained tonalites and the softer, more pelitic Loch Raven-Laurel rocks. The more massive, crystalline tonalites would be expected to soften less readily under a given strain rate and thus act as a buttress to the more accommodating metasedimentary rocks. Considerable strain would likely be focused along the contact. Another possibility is that shearing was initiated within incompletely crystallized parts of Kensington Tonalite as the latter was intruded as a succession of elongate sheets along the contact between the two tectonic motifs, perhaps in concert with increasing regional metamorphic grade. Still another consideration is the nature of the contact between the Loch Raven-Laurel motif and the Sykesville Formation. As noted earlier, although they share certain features, the two metasedimentary units differ sharply in several key respects; they appear to constitute distinctly different sedimentary packages that were probably deposited in different places or at different times within a very large basin. The contact may represent a former thrust surface, now completely reactivated and obscured by subsequent shearing. The possibility therefore exists that such a surface in and of itself would have constituted a fundamental regional heterogeneity along which localized strain softening may have been initially concentrated.

The RCSZ could not be traced north of the Kensington quadrangle (Figure 3; Drake, in press), nor is there any direct evidence for it in the nearly continuous exposures along the Patuxent and Patapsco Rivers somewhat further to the north. Current data suggest that the shear zone gradually diminishes northward, merging imperceptibly into a series of tight, north- to northwest-trending folds in several bodies of closely foliated Kensington Tonalite and surrounding metasedimentary rocks.

There is indirect evidence that the shear zone continues beneath the Coastal Plain south of the Potomac River. Aeromagnetic maps of that area exhibit a pronounced, north- to northeast-trending anomaly that aligns directly with the southernmost exposures of the eastern strand of the shear zone at the Zoo (Figure 1). The anomaly also coincides generally with a gravity contrast of about 3 to 5 milligals, which has been interpreted to be the faulted eastern contact of the Sykesville Formation (Daniels, 1980).

The magnetic anomaly continues southward essentially uninterrupted beneath the Coastal Plain for another 15-20 km, and strikes into a poorly exposed shear zone and fault that separates the Cambrian-age Chopawamsic Formation from the Occoquon Granite (Ordovician) to the west (Figure 1). Another nearby zone of sheared rocks bounds the east side of the Chopawamsic, separating it from the Late (?) Ordovician Quantico Formation. The shear zones bounding the Chopawamsic are poorly understood and could not be delineated in detail because they appear through the Coastal Plain cover only in very small, isolated, erosional inliers. They do appear to exhibit evidence for both sinistral and dextral slip, however (Heimgartner, 1995). Based on the ages of adjacent rock units, some of the ductile deformation could be as old as Early to Middle Ordovician, which is consistent with the tectonic history of the RCSZ. It thus seems possible that the shear zones that bound the Chopawamsic could be related, or perhaps contiguous with the RCSZ, and perhaps with the Eastern Piedmont fault system of Hatcher and others (1977), but there are insufficient data to establish a conclusive relationship.

Most of the post-Cretaceous thrust faults in the lower Rock Creek Valley are localized within rocks that were already strongly sheared and faulted along the RCSZ; their abundance in that area is probably attributable to the preexisting zone of weakness caused by Paleozoic faults. The accounts of Darton (1950; 1951) and others who observed the temporary exposures created during the development of adjacent neighborhoods suggest that there are many more such faults in this area that have not been recorded. The total amount of throw encompassed by this fault system could be considerable; the distribution of known faults suggests that the fault system might be an imbricate fan from a significant master thrust at depth. Additional subsurface data are needed to test this hypothesis. In any event, the late movement seen on these faults is comparable to that observed on similar faults elsewhere in the Coastal Plain (e.g., Mixon and Newell, 1977; Newell, 1984), and suggests ongoing tectonism along this part of the Fall Zone.

REFERENCES

Bassler, R.S., 1940, Geological exhibits in the National Zoological Park: Smithsonian Annual Report-1939, Publication 3565, p. 265-279.

Becker, J.L., Kunk, M.J., Wintsch, R.P., and Drake, A.A., Jr., 1993, Evidence for pre-Taconic metamorphism in the Potomac terrane, Maryland and Virginia: hornblende and muscovite ^{40}Ar-^{39}Ar results: Geological Society of America Abstracts with Programs, v. 25, p. 5.

Bell, T.H., 1978, Progressive deformation and reorientation of fold axes in a ductile mylonite zone: The Woodroffe Thrust: Tectonophysics, v. 44, p. 285-320.

Bell, T.H., 1986, Foliation development and refraction in metamorphic rocks: Reactivation of earlier foliations and decrenulation due to shifting patterns of deformation partitioning: Journal of Metamorphic Petrology, v. 4, p. 421-444.

Berthe, D., Choukroune, P., and Jegouzo, P., 1979, Orthogneiss, mylonite and noncoaxial deformation of granites: the example of the South Armorican Shear Zone: Journal of Structural Geology, v. 1, p. 31-42.

Bobyarchick, A.R., 1981, The eastern piedmont fault system and its relationship to Alleghanian tectonics in the southern Appalachians: Journal of Geology., v. 89, p. 335-347.

Bobyarchick, A.R., 1988, Location and geometry of Alleghanian dispersal-related strike-slip faults in the southern Appalachians: Geology, v. 16, p. 915-919.

Bobyarchick, A.R., and Glover, L., III, 1979, Deformation and metamorphism in the Hylas zone and adjacent parts of the eastern Piedmont in Virginia: Geological Society of America Bulletin, v. 90, p. 739-752.

Bromery, R.W., Gilbert, F.P., and others, 1963, Aeromagnetic map of the Kensington quadrangle, Montgomery County, Maryland: U.S. Geological Survey Geophysical Investigations Map GP-398, Scale 1:24,000.

Cloos, E., 1964, Structural geology of Howard and Montgomery Counties, in The geology of Howard and Montgomery Counties: Baltimore, Maryland Geological Survey, p. 216-261.

Cloos, E., and Cooke, C.W., 1953, Geologic map of Montgomery County and the District of Columbia: Maryland Department of Geology, Mines, and Water Resources, scale 1:62,500.

Costa, R.E., and Gates, A.E., 1992, Mylonitization of mylonites: Evidence for opening and closing of the Iapetus Ocean from the Ramapo fault zone: Geological Society of America Abstracts with Programs, v. 24, no. 3, p. 14.

Crowley, W.P., 1976, The geology of the crystalline rocks near Baltimore and its bearing on the evolution of the eastern Maryland Piedmont: Baltimore, Maryland Geological Survey Report of Investigations 27, 40 p.

Daniels, D.L., 1980, Geophysical-Geological Analysis of Fairfax County, Virginia: U.S. Geological Survey Open-File Report 80-1165, 64 p.

Darton, N.H., 1950, Configuration of the bedrock surface in the District of Columbia: U.S. Geological Survey Professional Paper 217, 42 p.

Darton, N.H., 1951, Structural relations of Cretaceous and Tertiary formations in part of Maryland and Virginia: Geological Society of America Bulletin, v. 62, p. 745-780.

Davis, G.L., Tilton, G.R., Aldrich, L.T., Wetherill, G.W., and Bass, N.M., 1960, The ages of rocks and minerals: Carnegie Institute Washington Yearbook 59, p. 147-158.

Drake, A.A., Jr., 1985a, Tectonic implications of the Indian Run Formation-a newly recognized sedimentary mélange in the northern Virginia Piedmont: U.S. Geological Survey Professional Paper 1324, 12 p.

Drake, A.A., Jr., 1985b, Metamorphism in the Potomac composite terrane, Virginia-Maryland: Geological Society of America Abstracts with Programs, v.17, no. 7, p. 566.

Drake, A.A., Jr., 1986, Geologic Map of the Fairfax Quadrangle, Fairfax County, Virginia: U.S. Geological Survey Geological Quadrangle Map GQ-1600, Scale 1:24,000.

Drake, A.A., Jr., 1987, Pre-Taconian deformation in the Piedmont of the Potomac Valley-Penobscotian, Cadomian, or both? *in* Contributions to Virginia Geology - VI (Harris Volume): Virginia Division of Mineral Resources Publication 74, p. 1-18.

Drake, A.A., Jr., 1989, Metamorphic rocks of the Potomac Terrane in the Potomac Valley of Virginia and Maryland: American Geophysical Union, 28th International Geological Congress, Field Trip Guidebook T202, Washington, D.C., 22 p.

Drake, A.A., Jr., in press, Geologic Map of the Kensington Quadrangle, Montgomery County, Maryland: U.S. Geological Survey Geological Quadrangle Map GQ-1774, Scale 1:24,000

Drake, A.A., Jr., and Fleming, A.H., 1994, The Dalecarlia Inrusive Suite and Clarendon Granite in the Potomac Valley, in Stratigraphic Notes, 1991-92: U.S. Geological Survey Bulletin 2060, p. 25-33.

Drake, A.A. Jr., and Froelich, A.J., 1986, Geologic Map of the Annandale Quadrangle, Fairfax and Arlington Counties, and Alexandria City, Virginia: U.S. Geological Survey Geological Quadrangle Map GQ-1601, Scale 1:24,000.

Drake, A.A. Jr., and Froelich, A.J., 1997, Geologic map of the Falls Church Quadrangle, Fairfax and Arlington Counties, Virginia and Montgomery County, Maryland: U.S. Geological Survey Geological Quadrangle Map GQ-1734, Scale 1:24,000.

Drake, A.A. Jr., and Lee, K.Y., 1989, Geologic map of the Vienna Quadrangle, Fairfax County, Virginia and Montgomery County, Maryland: U.S. Geological Survey Geological Quadrangle Map GQ-1670, Scale 1:24,000.

Drake, A.A., Jr., and Lyttle, P.T., 1981, The Accotink Schist, Lake Barcroft Metasandstone, and Popes Head Formation–Keys to an understanding of the tectonic evolution of the northern Virginia Piedmont: U.S. Geological Survey Professional Paper 1205, 16 p.

Drake, A.A., Jr., and Morgan, B.A., 1981, The Piney Branch

Complex–A metamorphosed fragment of the central Appalachian ophiolite in northern Virginia: American Journal of Science, v. 281, no.4, p. 484-508.

Drake, A.A., Jr., Sinha, A.K., Laird, Jo, and Guy, R.E., 1989, The Taconic orogen, *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 101-177.

Durrant, J.M., Sutter, J.F., and Glover, L., III, 1980, Evidence for an Alleghanian (Hercynian?) metamorphic event in the Piedmont province near Richmond, Virginia: Geological Society of America Abstracts with Programs, v. 12, p. 176.

Fellows, R.E., 1950, Notes on the geology of Rock Creek Park, District of Columbia: American Geophysical Union Transactions, v. 31, p. 267-277.

Fisher, G.W., 1963, The petrology and structure of the crystalline rocks along the Potomac River near Washington, D.C., Baltimore, Johns Hopkins University, unpublished Ph.D. dissertation, 241 p.

Fisher, G.W., 1970, The metamorphosed sedimentary rocks along the Potomac River near Washington, D.C., in Fisher, G.W., and others, eds., Studies of Appalachian geology, central and southern: New York, Interscience, p. 299-315.

Fisher, G.W., 1979, Stratigraphy and structure of the central Appalachian Piedmont, Maryland and Pennsylvania: A review of recent evidence in Wones, D.R., ed., Proceedings of the Caledonides in the USA: Virginia Polytechnic Institute Department of Geological Sciences Memoir 2, p. A6.

Fleming, A.H., Drake, A.A., and McCartan, Lucy, 1992, The Rock Creek shear zone–a major tectonic feature in the central Appalachian piedmont: Geological Society of America Abstracts with Programs, v. 24, no. 3, p. 21.

Fleming, A.H., Drake, A.A., and McCartan, Lucy, 1994, Geologic Map of the Washington West Quadrangle, District of Columbia, Montgomery County, Maryland, and Arlington County, Virginia: U.S. Geological Survey Geologic Quadrangle Map GQ-1748, scale 1:24,000.

Glover, L., III, Speer, J.A., Russell, G.S., and Farrar, S.S., 1983, Ages of regional metamorphism and ductile deformation in the central and southern Appalachians: Lithos, v. 16, p. 223-245.

Grauert, B., 1973, U-Pb isotopic studies of zircons from the Gunpowder granite, Baltimore County, Maryland: Carnegie Institution of Washington Yearbook 1972, p. 288-290.

Hatcher, R.D., 1989, Tectonic synthesis of the U.S. Appalachians, *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 511-535.

Hatcher, R.D., Jr., Howell, D.E., and Talwani, P., 1977, Eastern Piedmont fault system: Speculations on its extent: Geology, v. 5, p. 636-640.

Hatcher, R.D., Jr., Thomas, W.A., Geiser, P.A., Snoke, A.W., Mosher, S., and Wiltschko, D.V., 1989, Alleghanian orogeny, in Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 233-318.

Heimgartner, D., 1995, Geologic investigation of a ductile shear zone in the northern Piedmont of Virginia: Fairfax, Virginia, George Mason University, unpublished senior thesis, 23 p., plus 21 figures.

Hopson, C.A., 1964, The crystalline rocks of Howard and Montgomery Counties, *in* The geology of Howard and Montgomery Counties: Baltimore, Maryland Geological Survey, p. 27-215.

Horton, J.W., Jr., Drake, A.A., Jr., and Rankin, D.W., 1989, Tectonostratigraphic terranes and their Paleozoic boundaries in the central and southern Appalachians, *in* Dallmeyer, R.D., ed., Terranes in the circum-Atlantic Paleozoic orogens: Geological Society of America Special Paper 230, p. 213-245.

Lapham, D.M., and Bassett, W.A., 1964, K-Ar dating of rocks and tectonic events in the Piedmont of southeastern Pennsylvania: Geological Society of America Bulletin, v. 75, p. 661-668.

Mixon, R.B., and Newell, W.L., 1977, Stafford fault system: structures documenting Cretaceous and Tertiary deformation along the Fall Line in northeastern Virginia: Geology, v. 5, p. 437-440.

Muller, P.D., and Chapin, D.A., 1984, Tectonic evolution of the Baltimore Gneiss anticlines, Maryland, *in* Bartholomew, M.J., ed., The Grenville event in the Appalachians and related topics: Geological Society of America Special Paper 194, p. 127-148.

Muth, K.G., Arth, J.G., and Reed, J.C., Jr., 1979, A minimum age for high-grade granite intrusion in the Piedmont of the Potomac River gorge near Washington, D.C.: Geology, v. 7, p. 349-350.

Newell, W.L., 1984, Architecture of the Rappahannock Eastuary--Neotectonics in Virginia, *in* Morisawa, M., and Hack, J.T., eds., Tectonic Geomorphology: A proceeding volume of the 15th Annual Geomorphology series, p. 321-342.

O'Connor, J.V., 1982, Geological excursions through Rock Creek Valley, northwest Washington, D.C.: Geological Society of America Northeastern-Southeastern Section Meeting, Field Trip 8, University of the District of Columbia Geoscience Guidebook 3, 23 p.

O'Connor, J.V., 1989, Geological Exploration of the southern Rock Creek Valley in D.C.: American Geophysical Union, 28th International Geological Congress, Field Trip Guidebook T208, Washington, D.C., 12 p.

Pavlides, L., Stern, T.W., Arth, J.G., Muth, G.K., and Newell, M.F., 1982, Middle and upper Paleozoic granitic rocks in the Piedmont near Fredericksburg, Virginia: Geochronology: U.S. Geological Survey Professional Paper 1231-B, p. B1-B9.

Platt, J.P., 1979, Extensional crenulation cleavage: Journal of Structural Geology, v. 1, p. 95-96.

Prowell, D.C., 1983, Index of faults of Cretaceous and Cenozoic age in the eastern United States: U.S. Geological Survey Miscellaneous Field Studies Map MF-1269, scale 1:2,500,000.

Reed, J.C., Jr., and Jolly, Janice, 1963, Crystalline rocks of the Potomac River gorge near Washington, D.C.: U.S. Geological Survey Professional Paper 414-H, 16 p.

Sacks, P.E., Horton, J.W., Jr., and Stoddard, E.F., 1991, Hollister Fault Zone, eastern Piedmont of NC and VA: Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 122.

Seiders, V.M., Mixon, R.B., Stern, T.W., Newell, M.F., and Thomas, C.B., Jr., 1975, Age of plutonism and tectonism and a new minimum age limit on the Glenarm Series in the northeast Virginia Piedmont near Occoquan: America Journal of Science, v. 275, no. 5, p. 481-511.

Seiders, V.M., and Mixon, R.B., 1981, Geologic map of the Occoquon quadrangle and part of the Fort Belvoir quadrangle, Prince William and Fairfax Counties, Virginia: U.S. Geological Survey Miscellaneous Investigations Series Map I-1175, scale 1:24,000.

Sibson, R.H., 1977, Fault rocks and fault mechanisms: Journal of the Geological Society of London, v. 133, p. 191-213.

Sutter, J.F., Pavlides, L., Kunk, M.J., and Coresini, H., Jr., 1985, Late Paleozoic metamorphism and uplift in the Piedmont near Fredericksburg, Virginia: Geological Society of America Abstracts with Programs, v. 17, p. 138.

Valentino, D.W., Glover, L., III, Gates, A.E., and Hill, M.L., 1992, The role of transcurrent shear zones in the tectonic assembly of the central Appalachian Piedmont: Geological Society of America Abstracts with Programs, v. 24, no. 3, p. 82.

Wetherill, G.W., Tilton, G.R., Davis, G.L., Hart, S.R., and Hopson, C.A., 1966, Age measurements in the Maryland Piedmont: Journal of Geophysical research, v. 71, p. 2139-2155.

White, S.H., Burrows, S.E., Carreras, J., Shaw, N.D., and Humphreys, F.J., 1980, On mylonites in ductile shear zones: Journal of Structural Geology, v. 2, no. 1, p. 175-187.

Wright, J.E., Sinha, A.K., and Glover, L., III, 1975, Age of zircons from the Petersburg Granite, Virginia: With comments on belts of plutons in the Piedmont: American Journal of Science, v. 275, p. 848-856.

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HYDROLOGIC AND WATER-CHEMISTRY DATA FROM THE CRETACEOUS-AQUIFERS TEST WELL (BFT-2055), BEAUFORT COUNTY, SOUTH CAROLINA

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ABSTRACT

Test well BFT-2055 was drilled through the entire thickness of Coastal Plain sediments beneath central Hilton Head Island, South Carolina, and terminated in bedrock at a depth of 3833 feet. The well was drilled to evaluate the hydraulic properties of the Cretaceous formations beneath Hilton Head Island as a potential source of supplemental water to supplies currently withdrawn from the Upper Floridan aquifer. The intervals tested include sediments of the Cape Fear and Middendorf Formations. Results from aquifer tests indicate that the transmissivity of the formations screened ranges from 1300 to 3000 feet squared per day and an average hydraulic conductivity of about 15 feet per day. Formation-fluid pressure tests indicate that the potential exists for upward ground-water flow from higher fluid pressures in the deeper Cape Fear and Middendorf Formations to lower fluid pressures in the Black Creek Formation and shallower units. A flowmeter test indicated that greater than 75 percent of the natural, unpumped flow in the well is from the screened intervals no deeper than 3100 feet. Water-chemistry analyses indicate that the water sampled from the Middendorf and Cape Fear has about 1450 milligrams per liter dissolved solids, 310 to 1000 milligrams per liter sodium, and 144 to 1600 milligrams per liter chloride. Because these chloride concentrations would render water pumped from these aquifers as non-potable, it is unlikely that these aquifers will be used as a supplemental source of water for island residents without some form of pre-treatment. Similar chloride concentrations are present in some wells in the Upper Floridan aquifer adjacent to Port Royal Sound, and these chloride concentrations were the primary reason for drilling the test well in the Cretaceous formations as a possible source of more potable water.

INTRODUCTION

A thick sequence of Upper Cretaceous to Holocene, semi- to unconsolidated sediments comprise the Atlantic Coastal Plain beneath southeastern South Carolina. Of these sediments, the Tertiary age Upper Floridan aquifer of the regional Floridan aquifer system is the primary source of high quality (low dissolved solids) drinking water. Because this use is concentrated near the coast, however, there is concern that documented increases in saltwater encroachment at northern Hilton Head Island will constrain the continued reliance on this aquifer as a sole source of potable water (Landmeyer and Belval, 1996). A test well was drilled, therefore, to examine the possibility of using the Cretaceous formations beneath the Floridan aquifer system as an alternative source of fresher water that would not be impacted by saltwater encroachment. These Cretaceous formations include the Cape Fear, Middendorf, Black Creek, and Peedee Formations.

The test well drilled (BFT-2055) was completed through the entire thickness of Coastal Plain sediments beneath central Hilton Head Island, South Carolina, and terminated in bedrock at a depth of 3833 feet (ft). The wellhead is adjacent to Singleton Beach Road off U.S. Highway 278, which leads about ½-mile (mi) to a beach of the same name on the coast of the Atlantic Ocean (Figure 1). The well is approximately in the middle part of Hilton Head Island, adjacent to the coast. The topography is rela-

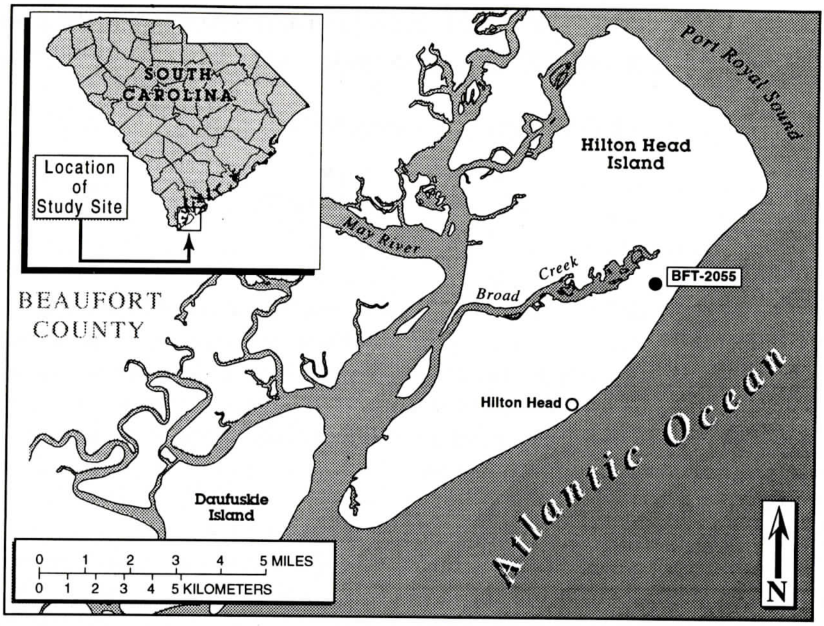

Figure 1. Location of test well, BFT-2055, and Hilton Head Island, Beaufort County, SC.

tively flat with an altitude no more than 10-ft above sea level. The location of the wellhead is latitude 32°11'29.42" N and longitude 80°42'14.06" W. The intervals investigated during drilling include sediments of the Cape Fear and Middendorf Formations. Geophysical logs run during drilling indicate that the Cretaceous Peedee and Black Creek Formations (beginning around 1685 and ending around 2770-ft below sea level, respectively) penetrated by the drilling (but not screened) consisted of low resistivity and low permeability (fine-grained) clays and silts (Temples and Engelhardt, 1997). Higher resistivity sands were encountered below a depth of 2780-ft below sea level; hence, the contact between the Black Creek Formation and the underlying Middendorf Formation is probably correlated with this depth. The thickness of these deeper sands (both the Middendorf and Cape Fear Formations) was determined by examining high-resolution dual-induction resistivity, spontaneous potential, gamma, compensated-neutron porosity, and gamma-density geophysical logs (Temples and Waddell, 1996). Temples and Waddell (1996) state that about 400 ft of sand was delineated between 2770 and 3833 ft, and that these sands are in separate intervals of thicknesses up to 19 ft. However, about 200 ft of these sands are in sequences less than 5-ft thick (Temples and Waddell, 1996).

Purpose and Scope

The purpose of this report is to present selected hydrologic and water-chemistry data obtained during the drilling of test well BFT-2055 in 1992. Data collected include aquifer characteristics and selected water chemistry of the Cretaceous formations encountered during drilling. The information presented here, particularly the limited water-chemistry data, is meant to supplement information provided by Snipes and others (1995), Temples and Waddell (1996), and Temples and Engelhardt (1997). These studies are particularly relevant, because limited information exists for Cretaceous-age water-bearing formations in this area of South Carolina.

As part of the overall test drilling, the scope of information presented in this report focuses on two items: (1) geologic cuttings and sidewall core samples for hydrologic and water-chemistry examination; and (2) formation-fluid pressure and aquifer characteristics of the water-bearing zones.

WELL CONSTRUCTION

Test well BFT-2055 was drilled to a depth of 3833 ft, initially cased and grouted to 900 ft, and subsequently reamed to accommodate screens after geologic and hydrologic testing were completed. The test well was an 18 x 8-inch (in) gravel-wall well with 24-in surface casing to a depth of 108 ft, 18-in intermediate casing grouted to 290 ft, and 12-in intermediate casing to 550 ft. An 8-in inner casing and screen line of 304 stainless steel was welded to the 12-in casing at 550 ft to a depth of 3708 ft.

The 18 screened intervals in the Middendorf and Cape Fear Formations were installed to cover the full thickness of each of the sand units determined by using geophysical logs and side-wall cores as being water-producing zones. The screened depth intervals are as follows; 2782 to 2794 ft, 2808 to 2816 ft, 2822 to 2840 ft, 2910 to 2920 ft, 2951 to 2960 ft, 2978 to 2992 ft, 3002 to 3010 ft, 3046 to 3054 ft, 3060 to 3068 ft, 3090 to 3104 ft, 3370 to 3382 ft, 3436 to 3446 ft, 3466 to 3484 ft, 3508 to 3516 ft, 3552 to 3560 ft, 3580 to 3590 ft, 3628 to 3638 ft, and 3678 to 3688 ft.

The sediments adjacent to the screened intervals were developed by a combination of three methods. The well was initially developed by horizontal jetting with freshwater. Secondly, an alternating schedule of pumping and recovery was performed using a test pump set at 340 ft below land surface. The final development was done by horizontal jetting with high-pressure freshwater treated with sodium hexametaphosphate.

Side-Wall Core Sample Collection

Test well BFT-2055 was drilled from land surface to the top of pre-Cretaceous rock using the mud-rotary drilling method. A continuous geologist log was prepared based on observations of the drill cuttings recovered at land surface during drilling operations. These cuttings were placed in plastic bags for preservation and storage in the South Carolina Subsurface Samples Repository at the S.C. Geological Survey, Columbia, S.C. Percussion side-wall cores of formation material were obtained at 239 discrete depths along the borehole. Each 1.5 in x 4 in side-wall core was lithologically described. A subset of core samples (14 from the 239 collected) were squeezed under pressure in a stainless steel press (Manheim, 1966) to obtain porewater for water chemistry.

Geology

Beaufort County is located in the southeastern part of the South Carolina part of the Atlantic Coastal Plain. The Coastal Plain sediments consist of semi- to unconsolidated clay, silt, sand, and some limestone and marl. These sediments of Upper Cretaceous to Holocene age form a wedge-shaped sequence that thickens from the Fall Line in the middle of the state toward the coast. The deeper Cretaceous sediments overly the erosional surface of a pre-Cretaceous peneplain consisting of metamorphic, igneous, and consolidated sedimentary rock.

Test well BFT-2055 was drilled through the entire thickness of the Coastal Plain sediments and ended in what is reported to be an altered volcanic rhyolite (Snipes and others, 1995). Geologic units encountered during drilling include, in ascending order, the Cape Fear, Middendorf, Black Creek, and Peedee Formations of late Cretaceous age; the Black Mingo Formation of Paleocene age; the Santee and Ocala Limestones of Eocene age (Figure 2); the Hawthorn Formation of Miocene age, and; the surficial deposits of Pleistocene-to-Holocene age (Gohn, 1992; Prowell, 1994).

The suite of geophysical logs made of the borehole included dual-induction resistivity, spontaneous potential, compensated neutron, gamma-density (Densilog), caliper, natural gamma, spectralog (spectral gamma), multipole array acoustilog, high resolution diplog, circumferential borehole imaging log, thin-bed analysis, clay analysis and shaly sand evaluation, litho-elastic properties, and complex reservoir analysis (refer to Temples and Waddell

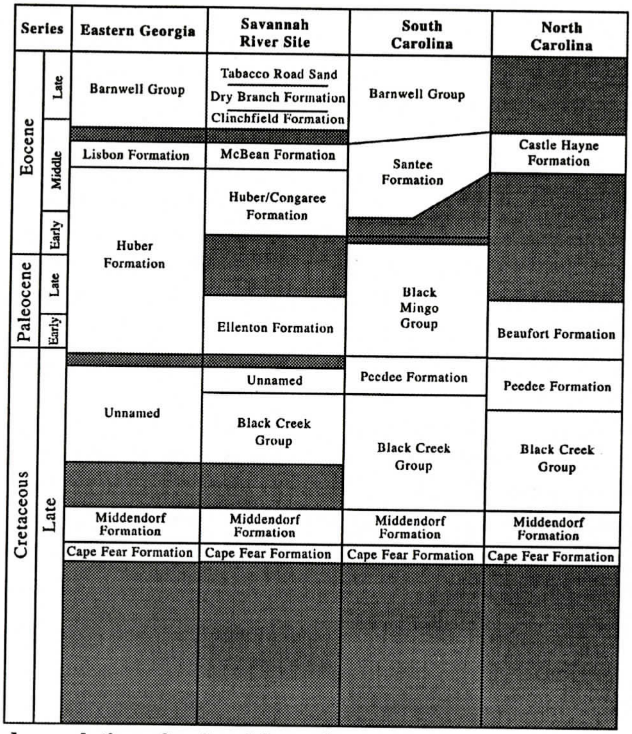

Figure 2. Generalized correlation of units of Late Cretaceous through Eocene age. (Modified from Prowell, 1994).

(1996) and Temples and Engelhardt (1997) for greater explanation).

HYDROLOGIC DATA

Hydrologic testing of the water-bearing formations encountered during drilling consisted of formation-fluid pressure testing, aquifer drawdown and recovery tests, and a borehole-flowmeter test. The aquifer tests included both constant discharge and step-drawdown tests.

Formation-Fluid Pressure Tests

Fluid pressure tests were obtained on fluid from formation material adjacent to the borehole wall at twenty-one depths in the Middendorf and Cape Fear Formations. A downhole formation tester (Formation Multi-Tester [FMT]) was used by Atlas Wireline. The FMT consists of a mechanical arm that can extend across the diameter of the borehole to formation material isolated above and below by packers. Valid pressure tests (7 of 21) from the Middendorf and Cape Fear Formations ranged from 242 to 168-ft above land surface, respectively.

Table 1. Formation-fluid pressure tests from Test Well BFT-2055, Hilton Head Island, SC, 1992

[+, above land surface; -, below land surface; (), questionable data]

Formation name	Depth (feet below land surface	Head (feet relative to land surface)
Santee Limestone	948	+18
Santee Limestone	1040	(-878)
Black Mingo	1160	+34
Black Mingo	1430	+35
Peedee	1728	+85
Black Creek	2535	+151
Middendorf	2879	+191
Middendorf	2914	+195
Middendorf	3164	+169
Middendorf	3364	(+242)
Middendorf	3378	+184
Middendorf/Cape Fear	3634	+168

Note: Initial shut-in pressures were measured and converted to hydraulic heads. Modified from Atlantic Testing and Engineering, 1992)

Therefore, there is a significant potential for an upward component of ground-water flow from the deeper Cape Fear and Middendorf Formations to overlying shallower aquifers (Table 1).

Aquifer Tests

Aquifer tests were performed on test well BFT-2055 to provide the hydraulic properties, specifically the transmissivity, of the Cretaceous formations screened in the borehole. Two aquifer tests were performed; a 38.5-hour (hr) test and a 76-hr test. The 38.5-hr test consisted of 4 discharge rates (or steps). Initially, the head in the well was about 155-ft above sea level. The 4 steps had discharge rates of 381, 461, 609, and 805 gallons per minute (gal/min), respectively. Discharge was measured by using a 6-in orifice, 8-in discharge pipe, and a manometer attached to the discharge pipe. The 72-hr test consisted of a constant discharge of about 700 gal/min for the majority of the test. The drawdown of the water level during the 72-hr test reached a maximum of about 328-ft below land surface.

The transmissivity of the Cape Fear and Middendorf Formation sediments adjacent to the screened intervals calculated from these aquifer tests ranges from about 1300 feet squared per day (ft^2/d) (R. Newcome, Jr., SC Water Resources Commission, written commun., 1993) to 3000 ft^2/d (Atlantic Testing and Engineering, 1992), depending upon the value of hydraulic conductivity (10 to 25 feet per day (ft/d)), thickness of aquifer material (combined thickness of sand units both less than and greater than 4-ft thick), and the particular phase of the aquifer test used to calculate transmissivity. In contrast, an average value of 190 ft^2/d (standard deviation of 145 feet squared per day, n = 28) was reported for sands between 2806 and 3748 ft in Temples and Waddell (1996). These reported transmissivity determinations do not account for water in the aquifer derived from leakage from adjacent confining units. Although the calculated transmissivity covers a broad range, the values are similar to those calculated for Cretaceous-age aquifer wells in other areas of South Carolina. In addition, the highest transmissivity values calculated are at least an order-of-magnitude lower than those representative of the Tertiary formations used for water supply in the same location.

Additional aquifer parameters were calculated from aquifer test data. The specific capacity ranged from about 2 gal/min per foot of drawdown to 10 gal/min per foot assuming a 70% well efficiency (Atlantic Testing and Engineering, 1992). The storage coefficient (S) was calculated for each screened water-bearing sand by using geophysical logs (porosities and thicknesses) and aquifer compressibilities (thicknesses and acoustic log). A storage coefficient of 9.6×10^{-6} was calculated as an average (standard deviation of 6.0×10^{-6}, n = 28) of the sands screened below 2770 ft (Middendorf and Cape Fear Formations) (Temples and Waddell, 1996).

Borehole-Flowmeter Test

A borehole-flowmeter test was performed on test well BFT-2055 by U.S. Geological Survey (USGS) personnel following completion of the aquifer tests. The well was flowing naturally at 253 gal/min during the test. The flowmeter test revealed that most of the flow to the well (up to 75%) was provided by the screened intervals between 2782 and 3104 ft (Figure 3). About 2 percent of the flow was from the 5 lower screens, or from 3508 to 3688 ft.

WATER-CHEMISTRY DATA

Water samples from water-bearing zones screened in the borehole were collected from 7 depths that provided accurate formation-fluid pressure tests. One water sample was collected from the Lower Floridan aquifer (Santee Limestone at 948 ft), one from the Black Mingo Formation (at 1430 ft), and 5 samples from the Middendorf Formation (at 2879, 2914, 3164, 3378, and 3634 ft, respectively). Porewater samples were collected from side-wall cores obtained at 14 depths.

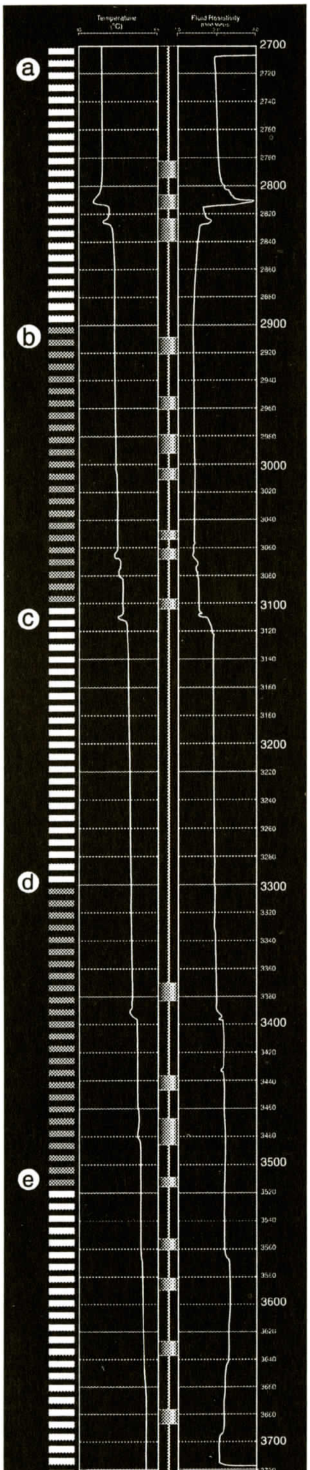

Figure 3. Borehole-flowmeter test results.

Summary of Selected Water-Chemistry Analyses

Five zones of aquifer material from depths below 2770 ft were used to obtain water-chemistry samples. Standard field parameters of temperature, pH, and specific conductance were measured in accordance with procedures described in Skougstad and others (1979) and Wood (1976). The water samples were obtained by using the downhole formation tester used during the formation-fluid pressure testing described earlier. Porewater from 14 side-wall cores taken from depths between 2665 and 2790 ft was analyzed for chloride and sulfate concentrations. Porewater results from this unscreened depth interval supplement water-chemistry results taken from screened intervals reported in Temples and Waddell (1996).

The analyses of a selected number of groundwater samples taken from test well BFT-2055 are shown in Tables 2-4. Water samples were analyzed by laboratories of the S.C. Department of Health and Environmental Control (SC-DHEC), S.C. Department of Natural Resources Water Resources Division (SCDNR-WRD), the USGS, and contracted private laboratories certified by the State of South Carolina.

Table 2. Field water-chemistry measurements from selected depths, Test Well BFT-2055, Hilton Head Island, SC, 1992.

[---, no data collected; μS/cm, microsiemens per centimeter]

Depth of sampling point (feet below land surface	Temperature (°C)	Specific conductance (μS/cm)	pH (standard units)
948	28.8	1000	8.2
1430	29.0	2100	9.7
2879	30.1	1150	7.4
2914	31.0	1300	8.0
3164	29.2	---	6.2
3634	29.8	1400	8.0

(Modified from Atlantic Testing and Engineering, 1992)
Note: Samples were collected using the Formation Multi-Tester as described.Note: Dissolved oxygen measurements ranged from 3.6 to 4.5 mg/L, but are considered to be an artefact of the sampling method and are subsequently not reported.

Table 3.Water-chemistry measurements obtained from formation fluid-pressure testing of Test Well BFT-2055, Hilton Head Island, SC, 1992.

[---, no data collected; <, less than; TDS, total dissolved solids; F, fluoride; Cl, chloride; SO4, sulfate; Si, silica; Na, sodium; Fe, iron; Ca, calcium; Mg, magnesium;Ba, barium; Al, aluminum]

Depth of sampling point (in ft below land surface)	TDS	F	Cl	SO_4	Si	Na	Fe	Ca	Mg	Ba	Al
	(All concentrations of constituents are in milligrams per liter, mg/L)										
2879	---	4.0	160	120	27	310	1.9	5.8	0.66	0.53	---
	---	---	144	132	---	---	---	---	---	---	---
2914	---	6.3	220	180	32	340	2.4	4.5	0.94	0.12	---
	---	---	205	188	---	---	---	---	---	---	---
3164	---	3.5	1600	46	20	1000	0.59	15	4.3	0.17	---
	---	---	1444	46	---	---	---	---	---	---	---
3378	1600	5.8	470	89	25	630	1.3	8.4	0.96	0.11	1.7
3634	1300	7.7	260	120	---	400	1.6	7.4	0.64	0.15	1.5
Composite	1800	5.7	600	18	---	750	0.34	6.1	1.8	0.04	<0.2

(Modified from Atlantic Testing and Engineering, 1992)

Field water-chemistry measurements from selected intervals are presented in Table 2. The average temperature between 948 and 3634 ft was 29.7°C. The average specific conductance for the same depth interval was 1390 microsiemens per centimeter (µS/cm). The average pH of all the water-chemistry samples collected was 7.9. Dissolved oxygen measurements ranged from 3.6 to 4.5 mg/L, but are considered to be an artifact of the sampling method and are subsequently not discussed.

Water-chemistry measurements from the formation-fluid pressure tester are presented in Table 3. Total dissolved solids concentrations ranged between 1600 mg/L at 3378 ft and 1300 mg/L at 3634 ft. Concentrations of fluoride ranged from 3.5 to 7.7 mg/L, and concentrations of chloride ranged from 144 to 1600 mg/L. The highest chloride values measured were for the sample at 3164 ft. Average concentrations of sulfate, silica, iron, calcium, magnesium, barium, and aluminum were about 115, 26, 1.5, 8.2, 1.5, 0.2 and 1.6 mg/L, respectively. Like chloride, sodium had the highest reported concentration (1000 mg/L) at the depth of 3164 ft. The average sodium concentration was 536 mg/L.

Water-chemistry measurements of porewater from 14 side-wall cores are presented in Table 4. Chloride concentrations ranged from 425 to 662 mg/L, and sulfate ranged from 149 to 493 mg/L. Because these chloride concentrations would render any water pumped from these depths as being non-potable, it is unlikely that these aquifers will be used as a supplemental source of water for island residents without some form of treatment. Ironically, the levels of chloride measured at these depths in the Cretaceous formations are similar to levels of chlo-

Table 4.Water-chemistry measurements of pore-water squeezed from 14 side-wall cores from Test Well BFT-2055, Hilton Head Island, SC, 1992.

[mg/L, milligrams per liter]

Depth to sampling point (in feet below land surface)	Chloride (mg/L)	Sulfate (mg/L)
2665	553	347
2692	526	149
2702	433	237
2722	567	239
2724	425	189
2728	456	214
2735	662	231
2740	569	209
2752	523	191
2757	559	159
2762	662	493
2765	611	170
2782	517	170
2790	556	271

Note: Drilling fluid had 386 mg/L chloride and 213 mg/L sulfate.

ride in the Upper Floridan aquifer, the initial reason for drilling the test well.

SUMMARY

Selected data collected from the test water well drilled in 1992 at Hilton Head Island, Beaufort County, South Carolina, are presented. Test well BFT-2055 (Beaufort-2055), located on central Hilton Head Island, South Carolina, was drilled through the entire thickness of Coastal Plain sediments and terminated in the underlying bedrock at a depth of 3833 feet. Aquifer tests indicate that the transmissivity of the formations screened ranges from 1300 to 3000 feet squared per day (depending on the method used) and an average hydraulic conductivity of about 15 feet per day. Formation-fluid pressure tests indicate that there is upward flow from higher fluid pressures in the deeper Cape Fear and Middendorf Formations to lower fluid pressures in the Black Creek Formation and shallower units. A flowmeter test indicated that greater than 75% of the natural, unpumped flow in the well is from the screened intervals above 3100 feet. Water-chemistry analyses indicate that the water sampled from the Middendorf and Cape Fear sands has about concentrations of dissolved solids, sodium, and chloride near 1450, 310 to 1000, and 144 to 1600 milligrams per liter, respectively.

ACKNOWLEDGMENTS

The data were collected as part of the drilling of the deepest test water well in South Carolina. As such, many people in a variety of private organizations and State and Federal agencies cooperated in this study, and are too numerous to mention here. Specifically for this report development, however, we thank Anthony Mancini and B.C. Spigner (formerly with Atlantic Testing & Engineering), Camille Ransom, III (SCDHEC, formerly with S.C. Department of Natural Resources Water Resources Division), Tom Temples (U.S. Department of Energy), and Mike Waddell (Earth Science Resource Institute).

REFERENCES CITED

Atlantic Testing & Engineering, 1992, Phase I report, Cretaceous aquifer test well, Hilton Head, South Carolina: AT & E report 92-1001.

Gohn, G.S., 1992, Revised nomenclature, definitions, and correlations for the Cretaceous formations in USGS-Clubhouse Crossroads #1, Dorchester County, South Carolina: U.S. Geological Survey Professional Paper 1518, 39 p.

Landmeyer, J.E., and Belval, D.L., 1996, Water-chemistry and chloride fluctuations in the Upper Floridan aquifer in the Port Royal Sound area, South Carolina: U.S. Geological Survey Water-Resources Investigations Report 96-4102, 106 p.

Manheim, F.T., 1966, A hydraulic squeezer for obtaining interstitial water from consolidated and unconsolidated sediments: U.S. Geological Survey Professional Paper 550-C, p. C256-261.

Prowell, D.C., 1994, Preliminary geologic map of the Barnwell 30' x 60' quadrangle, South Carolina and Georgia: U.S. Geological Survey Open-File Report 94-673, 39 p, 1 plate.

Skougstad, M.W., Fishman, M.J., Friedman, L.C., Erdmann, D.E., and Duncan, S.S., 1979, Methods for the analyses of inorganic substances in water and fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chapter A, 626 p.

Snipes, D.S., Kidd, N.B., Warner, R.D., Hodges, R.A., Price, V., Jr., and Temples, T.J., 1995, An initial petrographic and geochemical study of a rhyolitic rock recovered from test well #1, Hilton Head, South Carolina: South Carolina Geology, v. 38, p. 53-60.

Temples, T.J., and Waddell, M.G., 1996, Application of petroleum geophysical well logging and sampling techniques for evaluating aquifer characteristics: Ground Water, v. 34, no. 3, p. 523-531.

Temples, T.J., and Engelhardt, Don, 1997, Stratigraphy, depositional environments and sequence stratigraphy of the Upper Cretaceous in the Hilton Head Island test well #1, Beaufort County, South Carolina: Southeastern Geology, v. 36, no. 4, p. 177-186.

Wood, W.W., 1976, Guidelines for collection and field analysis of ground-water samples for selected unstable constituents: U.S. Geological Survey Techniques of Water-Resources Investigations, book 1, chapter D2, 24 p.

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LATE MAASTRICHTIAN SEDIMENTS ON THE NORTH FLANK OF THE CAPE FEAR ARCH, NORTH CAROLINA

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ABSTRACT

Olive gray very fine to fine grained, poorly indurated, argillaceous, dolomitic quartz wacke occurring disconformably above the Rocky Point Member of the Peedee Formation (Cretaceous) and below the Castle Hayne Limestone (Eocene), respectively, is designated the Island Creek Member of the Peedee Formation. The holostratotype of the Island Creek is an exposure at the Martin Marietta-Ideal Quarry in northern New Hanover County where 60 cm of the unit are exposed. Parastratotype sections are designated as the USGS LEA -1A-79 core hole in southern Pender County, where the unit is almost 11 m thick, and the east bank of the Northeast Cape Fear River at Hilton Park, Wilmington, where the unit is about 3 m thick. In southern New Hanover County, the unit reaches almost 15 m. A characteristic late Maastrichtian calcareous nannofossil flora correlating to Cretaceous nannofossil zones CC25-26 occurs in the Island Creek. Characteristic nannofossils include: *Micula decussata*, *Microhabdulus undosus*, *M. decoratus*, *Lithraphidites quadratus*, *Arkhangelskiella cymbiformis*, *Cribrosphaerella erhrenbergi*, *Prediscosphaera cretacea*, and abundant *Thoracosphaera* spp. Mega- and microfauna suggest deposition in a normal marine, aerobic environment, below storm wave base.

Dolomite, which comprises up to 53% by volume of the Island Creek Member, has $\delta^{18}O$ and $\delta^{13}C$ values that cluster around +3.5 ‰ and -0.3 ‰ relative to PDB, respectively. These values and dolomite crystal morphology suggest that elevated salinity existed in the sediment for a short period of time after deposition of the Island Creek and is responsible for dolomite formation.

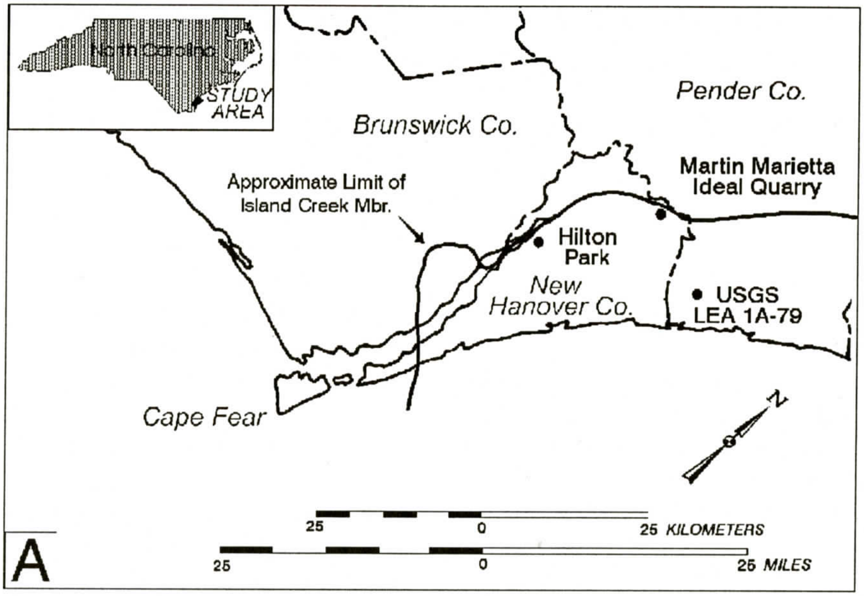
INTRODUCTION

The purpose of this paper is to define and describe the Island Creek Member of the Peedee Formation, a new late Maastrichtian unit that occurs in Brunswick. New Hanover, Pender, and Onslow Counties, N. C. (Figure 1). The unit occurs between the Early Maastrichtian Rocky Point Member of the Peedee and the middle Eocene Castle Hayne Limestone. The Island Creek Member is correlated to the Late Maastrichtian on the basis of calcareous nannofossils, and therefore, represents the youngest Cretaceous strata thus far recognized in the southeastern Atlantic Coastal Plain.

This paper also describes a distinctive dolomitic lithology that occurs in the Island Creek Member and suggests possible mechanisms for its origin and occurrence. Other reported dolomite occurrences in the Coastal Plain of the Carolinas (Cunliffe, 1968; Baum, 1977, Harris *et al.*, 1977; McLaurin, 1995; McLaurin and Dockal, 1995) are of more limited extent and all occur in younger strata (Paleocene to Miocene). The Island Creek dolomite has an unusual crystal morphology, which is similar in occurrence to hexagonal-like dolomite crystals reported from Recent supratidal evaporite flats of the Ojo de Liebre Lagoon, Baja California, Mexico (Pierre *et al.*, 1984).

HISTORICAL BACKGROUND

Cunliffe (1968) recognized dark muddy sediments in northern New Hanover County above



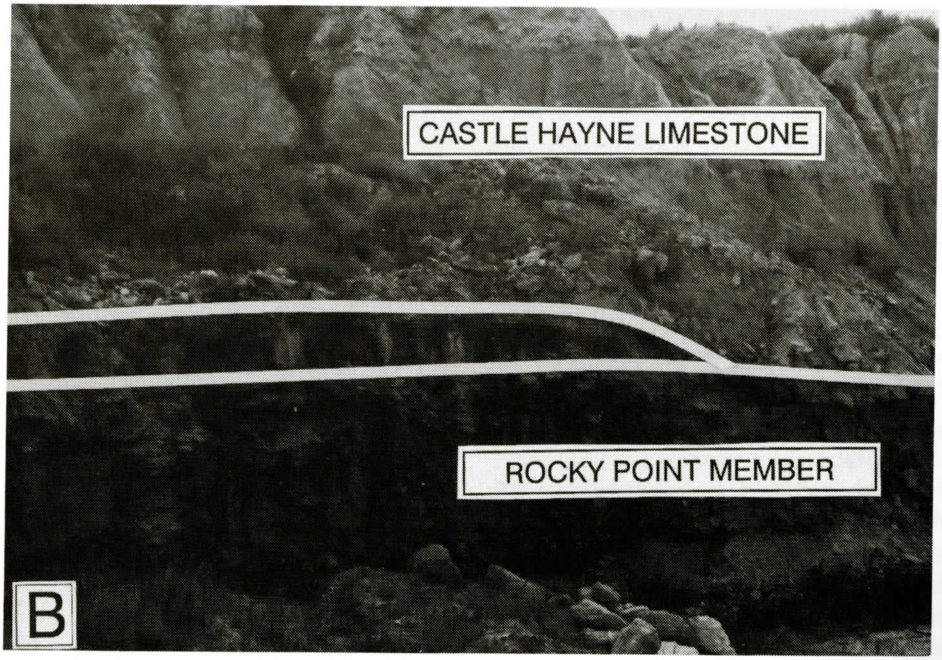


Figure 1. A) Location of the three sections studied that contain the Island Creek Member of the Peedee Formation. The holostratotype is the Martin Marietta-Ideal Quarry in New Hanover County (see B). The USGS LEA 1A-79 core hole (Pender County) and the exposure at Hilton Park (New Hanover County) are designated parastratotypes. B) Photograph of the holostratotype illustrating the Cretaceous Rocky Point Member of the Peedee Formation and the Eocene Castle Hayne Limestone; the Island Creek Member occurs between the two units (east side of the Martin Marietta-Ideal Quarry, unit 0.6 m thick).

a sandy limestone (Rocky Point Member of the Peedee Formation) and below the Castle Hayne Limestone. Although he did not name or map the unit, he suggested that the sediments were Cretaceous in age. Harris (1975, 1978) mapped the Maastrichtian Rocky Point Member in southeastern North Carolina, recognizing that it contained four distinct lithofacies: lower quartz arenite; upper sandy pelecypod biosparrudite; sandy, pelecypod biosparite; and sandy biosparite. In addition, he recognized unnamed friable, sandy sediments between the Rocky Point Member and the overlying Eocene Castle Hayne Limestone in New Hanover, Pender and Onslow Counties. He indicated that the unnamed sediments were lithologically similar to the typical Peedee Formation and interpreted them as a downdip lithofacies of the Rocky Point. Harris et al. (1986a) recognized and discussed a dolomitic sand lens, which ranged to 2 m in thickness between the Rocky Point Member and the Castle Hayne Limestone at the Martin Marietta-Ideal Quarry, New Hanover County, and indicated that it contained late Maastrichtian nannofossils. Sohl and Owens (1992) also recognized a Cretaceous unit on top of the Rocky Point Member, and confirmed the suggestion by Harris (1975) that sediments exposed on the east bank of the Northeast Cape Fear River at Hilton Park, Wilmington, were younger than the Rocky Point Member. Based on the megafauna, Sohl and Owens (1992) assigned these sediments to the [WBH1] *Haustator bilira* Assemblage Zone, which is the youngest Cretaceous molluscan zone recognized in North Carolina.

MATERIALS AND METHODS

Bulk samples were collected primarily from three locations: Martin Marietta-Ideal Cement Quarry; exposures along the Northeast Cape Fear River at Hilton Park; and the USGS LEA 1A-79 corehole (Figure 1). Thin sections were prepared from samples that were first impregnated with blue-dyed epoxy. Most thin sections were one-half stained with Alizarin red-S and potassium ferricyanide, according to the method of Dickson (1966). A 300-point modal analysis was made on each thin section. At the stratotype section in the Martin Marietta-Ideal Quarry, five samples were collected at about one-half meter intervals from the base to the top of the unit (Figure 2). Dolomite was separated from each of these five samples and evaluated for oxygen and carbon isotopes in the stable isotope laboratory at Southern Methodist University. Whole sample strewn slides of 28 samples from the Ideal Quarry, Hilton Park exposure, and LEA-1A-79 core were prepared and examined for calcareous nannofossils.

TYPE SECTION DEFINITION

Figure 1 shows the known extent of the Island Creek Member. The type locality is designated as the Martin Marietta-Ideal Cement quarry, northern New Hanover County, N.C., USGS Scotts Hill 7.5-minute quadrangle (N34° 22', W77° 50'). The quarry is east of the town of Castle Hayne between the Northeast Cape Fear River and State Route 1002. The holostratotype section of the Island Creek Member is the east side of the Martin Marietta/Ideal Cement quarry where up to 60 cm of the unit was exposed in 1985 (Figure 2). About one meter of the unit is currently exposed in an abandoned pit on the southeast side of the Ideal Cement quarry. Parastratotype sections include the interval between -168' to -132.5' in the U.S. Geological Survey LEA-1A-79 core hole located on the south side of N.C. Highway 210, just west of its intersection with U.S. Highway 17, Pender County (N34°22'29" W77°43'40"); and along the east bank of the Northeast Cape Fear River at Hilton Park, New Hanover County (N34°15'30", W77°56'51"). The name Island Creek is taken from the small tributary of the Northeast Cape Fear River (New Hanover-Pender County line) that is located just east of the quarry. At the type section, the Island Creek Member occurs disconformably above the Rocky Point Member of the Peedee Formation and disconformably below the Eocene Castle Hayne Limestone (Figure 2). The interval designated in the LEA-1A-79 core hole is the same interval illustrated by Harris (1978, Figure 3) on the mechanical log from the N.C. Oil and Gas

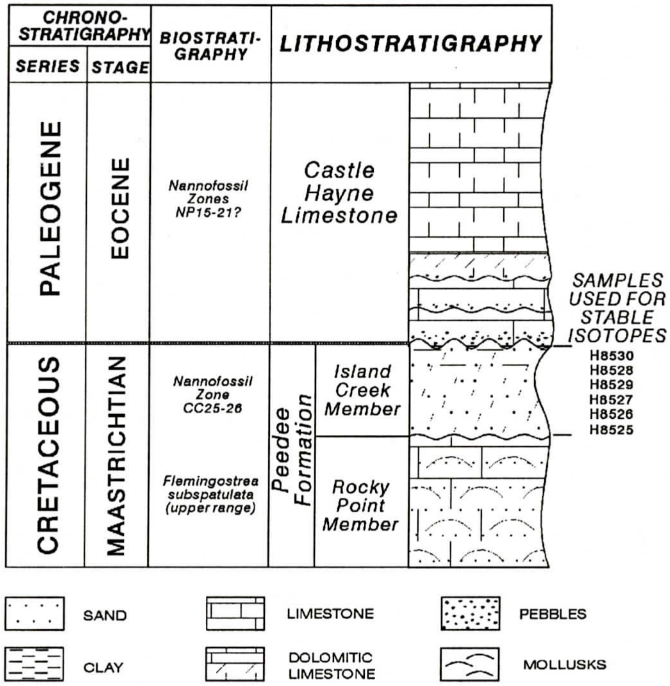


Figure 2. Columnar section of the holostratotype, Martin Marietta-Ideal Quarry.

#1 Lea as Peedee Formation.

The top of the Island Creek Member at the type section is a well developed erosion surface that separates upper Cretaceous strata from middle Eocene strata. At some locations, the lowermost beds of the overlying Castle Hayne Limestone contain reworked Cretaceous nannofossils, dolomite crystals, and Paleocene and Cretaceous lithoclasts. Consequently, the thickness of the Island Creek Member can vary significantly over short distances. The member ranges from a feather edge in northeastern New Hanover and northern Brunswick Counties, to a thickness of over 13 m in southern Onslow County, and over 15 m in southeastern New Hanover County (Harris, 1978).

The Island Creek Member is predominantly an olive gray (5 Y 4/1), well sorted, very fine to fine grained, poorly indurated, bioturbated, argillaceous, dolomitic quartz wacke (sensu Dott, 1964). Dolomite euhedra make up 1% to 53% by volume of the unit, with crystals ranging from 0.01 mm to 0.11 mm in diameter. The primary detrital component is quartz.

The Island Creek Member contains a characteristic late Maastrichtian calcareous nannofossil assemblage, which includes *Micula decussata*, *Microhabdulus undosus*, *M. decoratus*, *Lithraphidites quadratus*, *Arkhangelskiella cymbiformis*, *Cribrosphaerella erhrenbergi*, *Prediscosphaera cretacea*, and abundant *Thoracosphaera* spp. This assemblage correlates to Cretaceous nannofossil zones CC25-26. Foraminifers are abundant and well preserved, but as yet are unstudied.

PETROGRAPHY

The Island Creek is bioturbated throughout, and generally has a mottled appearance in outcrop. On a microscopic scale, bioturbation is marked by preferred alignment of the long axes of the quartz grains tangential to the central area of individual burrows. Non-burrowed sediment exhibits preferred orientation of detrital grains, and is characterized by apparent shrinkage pores elongated parallel to the preferred orientation of the long axis of the detrital grains. The

Table 1. Modal analysis of thin sections from the Island Creek Member of the Peedee Formation. Sample numbers beginning with 97-HP were collected at Hilton Park, and 95-IQ, H, D, RL and ICQ at the Martin Marietta-Ideal Quarry.

SAMPLE**	Quartz	Feldspar	Muscovite	Chlorite	Glaucony	Pyrite	Phosphorite	Other Detrital	Bioclasts	Dolomite	Micrite/Matrix	Porosity
ICQ-KD1	27	1	<1	1	<1	2	<1	<1	6	10	37	15
ICQ-KD2	29	1	<1	1	2	1	<1	-	4	16	35	12
RL314	23	1	<1	1	1	1	-	1	3	21	30	18
D86003	32	1	Tr	<1	1	1	-	1	-	23	27	16
H8528	19	1	Tr	<1	<1	1	-	-	Tr	35	26	19
H8527	10	<1	<1	Tr	<1	<1	-	-	-	53	13	23
95-IQ-5	24	1	Tr	1	<1	<1	-	-	-	26	20	27
95-IQ-4	23	2	Tr	Tr	1	1	-	-	-	35	21	17
95-IQ-3	24	2	Tr	1	1	1	<1	-	Tr	42	15	14
95-IQ-2	33	2	<1	<1	1	1	<1	-	-	30	14	17
97-HP-4	25	<1	Tr	1	1	<1	Tr	1	3	19	68	36
97-HP-3	28	2	<1	1	1	1	<1	1	10	8	55	22
97-HP-2	26	<1	<1	<1	2	1	Tr	1	13	<1	55	17
97-HP-1	29	<1	1	Tr	1	2	<1	2	5	2	51	20

** Sample numbers are referenced to location in Methods section of manuscript.

general character of the non-burrowed portion suggests that the sediment package, prior to burrowing, was a laminated or thin-bedded mud with alternating laminae of argillaceous material and fine sand.

Quartz is the primary detrital component comprising 7% to 33% by volume (Table 1). Two types are present: a very fine to fine grained, angular, discoidal to roller, monocrystalline variety; and a medium to coarse grained, subangular to subrounded, roller to spherical, monocrystalline variety. The ratio of the coarser to finer variety is 1:50. Grains of both types frequently contain an assortment of inclusions including rutile needles. The coarser variety of quartz infrequently exhibits undulatory extinction. Both varieties are very similar to the quartz grains of the underlying strata, except that those of the Rocky Point Member are, on the whole, slightly larger for both types. The Island Creek Member also contains a greater abundance of inclusion-rich quartz grains than the Rocky Point Member.

Orthoclase and plagioclase are present although orthoclase is predominant. Together they comprise less than 2% of the sediment (Table 1). Grains are angular and of the same size range as the finer variety of quartz. Some feldspar grains appear slightly etched while others have minor secondary intraparticle porosity. Muscovite occurs as thin plates 0.05 to 0.5 mm in maximum diameter. The larger muscovite grains exhibit delamination and the subsequent development of intraparticle porosity. Chlorite occurs as grains of variable shape ranging from 0.02 to 0.5 mm diameter. Based on color and pleochroic character, more than one type of chlorite is present. Most grains exhibit weathering as indicated by delamination and intraparticle porosity. Glauconite occurs as ellipsoidal grains with a diameters from 0.1 to 0.5 mm. Some glauconite grains display post-depositional fragmentation. Detrital phosphorite occurs as irregular-shaped, amorphous brown grains, less than 0.5 mm in diameter; these typically contain pyrite inclusions.

Non-calcareous bioclasts include small fish teeth, 0.3 to 1.0 mm in diameter, and very small and delicate bone fragments. Some bone fragments are smaller than the quartz grains, and many of the bone fragments appear to have been fractured and crushed *in situ*. A few pyritized grains appear to have been organic material or woody fragments.

Calcareous bioclasts include, in order of relative abundance: foraminifers, echinoderm plates, pelecypod shells and shell fragments, bryozoans, coralline red algae, ostracods and a brachiopod. However, most samples collected at or near the type section are devoid of calcareous bioclasts. Planktonic and benthic foraminifers are present and range in diameter from 0.05 to 0.3 mm. Several types of test structure were recognized including arenaceous agglutinate, microgranular, hyaline calcareous having perforate radial walls, and hyaline calcareous tests with perforate granular walls. Test cavities are generally empty of sediment, but some tests contain varying amounts of porosity-reducing bladed calcite. Echinoderm plates range in size from 0.1 to 0.7 mm diameter. Most have an irregular or non-descript shape, but a few do exhibit the more typical circular or rectangular shape in cross section. The plates are only partially permineralized and in two of the samples, the permineralization material seems to be ferroan calcite. Pelecypod shell fragments range from 0.04 mm to 0.2 mm in thickness and up to 5 mm in length. Calcitic foliated and aragonitic cross-lamellar microstructures occur, suggesting the presence of at least two different taxa; however, in hand samples only one unidentified species was recognized. No pelecypod specimens appear to be in growth position. Fragments of a cheilostome bryozoan, tentatively identified as *Periporesella* sp., were found in several samples. The bryozoan fragments range from 0.5 to 2 mm in diameter and are well preserved. A second encrusting bryozoan type, possibly a cyclostome, is evident in a hand specimen where the zoarium appears as a hemisphere 4 mm in diameter. Disarticulated fragments of coralline red algae up to 3 mm in diameter were found in two samples. They are generally poorly preserved, have minor silicification in the interior, and a glauconite accumulation on the exterior as well as within some of the cell structures near the outer margins. A single punctate brachipod fragment, a few millimeters in length, was observed having the primary and secondary shell layers preserved. The crystals of the primary layer have short bladed calcite syntaxial overgrowths projected into the adjacent pore space.

The matrix is a cryptocrystalline material that appears grayish brown in thin section in plain light. In most samples the matrix fails to take the Alizarin red-S stain suggesting a lack of calcite, yet in some places it takes the stain, but not uniformly. X-ray diffraction analyses suggest that illite is present in the matrix material, but the results are inconclusive. The dark color of the sediment suggests that the matrix may contain organic debris. The matrix makes up 13 to 68% of the volume of the sediment. The wide variation reflects the variable degree of bioturbation that seems to have in part removed matrix material. For thė purposes of modal analysis, any detrital grain less than 0.01 mm in diameter was counted as matrix.

Secondary minerals include pyrite, quartz, calcite, and dolomite. Pyrite occurs as discrete grains, 01. to 0.4 mm in diameter, and as spherical framboids less than 0.01 mm in diameter. The discrete grains appear to be pyritized organic material. The framboids occur as loose clusters frequently associated with bioclasts. Secondary calcite is limited to minor permineralization of some bioclasts and very small-bladed crystals on the surfaces of a few bioclasts. Minor quartz in the form of chalcedony has replaced parts of a few of the bioclasts.

The Island Creek Member contains up to 53% dolomite euhedra by volume. Crystals range from 0.01 mm to 0.11 mm in diameter. For the most part they are poorly formed euhedra, especially the smaller ones. In thin section many crystals appear to be hexagonal (Figure 3a and 3b), however this results from penetration twins having two corners of the crystal displaying a swallow-tail shape as though two rhombohedra have been fused together. Under crossed-polarized light no evidence of crystal lattice rotation is evident. The euhedra contain much foreign material and have a weak sense of zoning (Figure 3a). The zoning is more evident in the larger crystals, which develop a more regular, well formed rhombohedral shape. In addition, some of the larger crystals have a well formed almost lipid rhombohedral core surrounded by a zone of inclusion-rich material that has a poorly formed rhombohedral surface morphology. Some of the dolomite crystals also have secondary intracrystalline porosity that seems to reflect preferential dissolution of a specific zone. X-ray diffraction and X-ray dispersion suggests that the dolomite may be ferroan, although staining with potassium ferricyanide was inconclusive. The dolomite typically occurs as pore fillings, or within and displacing the matrix. Dolomite crystals also grow on the surfaces of bioclasts (Figure 3b),

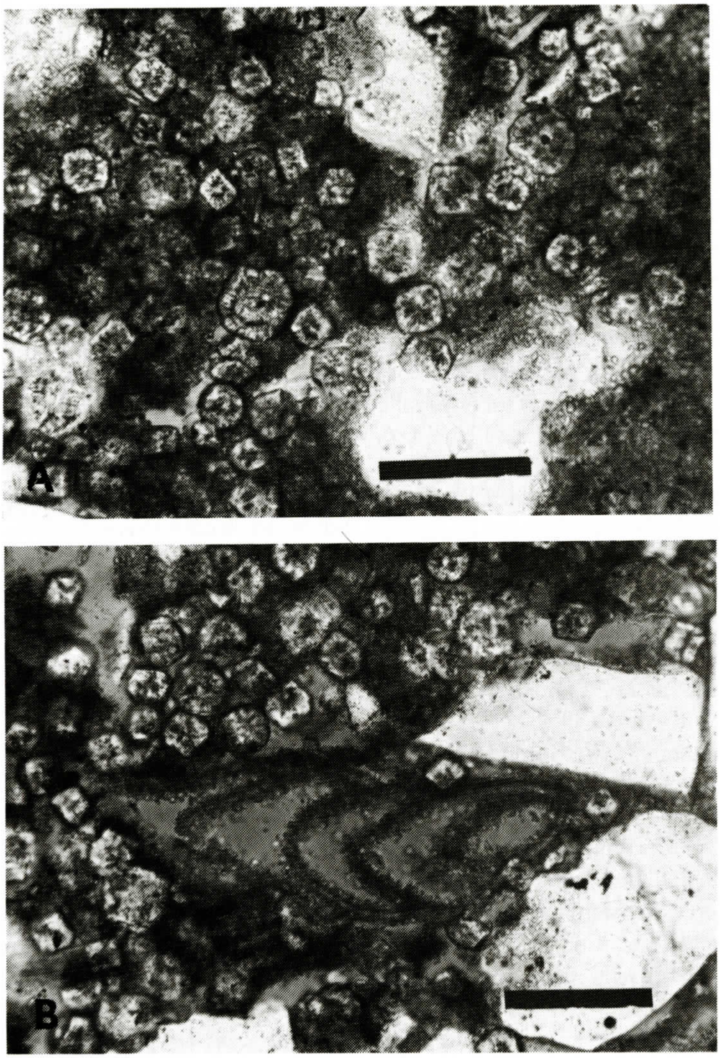


Figure 3. Typical hexagonal-like dolomite crystals from the Island Creek Member at the Martin Marietta-Ideal Quarry; light colored grains are typical quartz grains. A) Note the apparent zoning of some of the crystals and the abundance of included material; B) Dolomite crystals on and around a Foraminifera with no indication of replacement. Scale bars equal 0.08 mm.

but there is no clear evidence of replacement or cross cutting of the calcite bioclasts.

The distribution of dolomite varies vertically and horizontally within the member. Dolomite crystal size grades from finer at the bottom of the unit to larger at the top, whereas none of the other rock components exhibit any grain size gradations. Dolomite crystal size is inversely correlated with percent of calcite bioclasts. The volume percent of dolomite also increases upward in the unit. This is especially evident at the Hilton Park section where the base of the unit contains 2% dolomite, the mid portion 8%, and the top 19%. Dolomite percent also varies laterally. For example, the Martin Marietta-Ideal Cement locality contains the most dolomite (10 to 53%), the Hilton Park locality the least dolomite (1 to 19%), and the LEA-1A-79 core, though more similar to the Ideal Cement Quarry section, contains more calcite and smaller dolomite crystals.

Thin section porosity is largely interparticle and ranges from 12% to 36% (Table 1). Most calcareous bioclasts have intraparticle porosity. In foraminifers and echinoderm fragments this may be slightly reduced by secondary bladed calcite. The occasional bryozoan and ostracod shell exhibits no intraparticle porosity reduction. Most of the chlorite grains, some of the muscovite grains, and a very few of the feldspar grains exhibit some degree of secondary intraparticle porosity development. Samples that lack calcareous bioclasts exhibit what appears to be moldic porosity after bioclasts. All pore types are reduced by the growth of the dolomite. Some of the larger dolomite euhedra have secondary intracrystalline porosity. Shrinkage porosity, especially around quartz and glauconite grains, is common throughout, and is the dominant pore type in some regions. This type of porosity is not reduced by dolomite formation. In general, the pores appear to be well connected.

STABLE ISOTOPES

The $\delta^{18}O$ values for the dolomite cluster around +3.5 ‰, relative to the Peedee belemnite (PDB) standard, and exhibit no systematic variation within the bed or with any other dolomite parameter (Table 2). The oxygen isotopic analysis of the single calcite sample is heavy (+2.2) relative to "least-altered" marine invertebrate carbonate tests and marine cements of Cretaceous age, which exhibit $\delta^{18}O$ values ranging between -2.63 ‰ and +0.9 ‰ (Allan and Wiggins, 1993, Wilson and Opdyke, 1996). The equilibrium value for dolomite that has replaced calcite is approximately 3.0 ‰ (Land, 1980). Cretaceous dolomite, which is replacing typical Cretaceous marine invertebrate carbonate tests, should therefore have $\delta^{18}O$ values between +0.4 ‰ and +3.9 ‰. The dolomite in the Island Creek falls to the heavy side of this range. However, the dolomite of the Island Creek lacks any indication that it is of replacement origin and petrographically seems to occur as a simple porosity-reducing authigenic precipitate. The fractionation of oxygen isotopes between authigenic dolomite and the water from which it precipitated is given as: $10^3 \ln \alpha_{\text{dolomite-water}} = 2.78 \times 10^6 T^{-2} + 0.91$ (Land, 1985). Dolomite formed as an authigenic precipitate from modern normal marine water at 25° C should have a $\delta^{18}O$ value near +2.2 ‰. If normal marine water is adjusted for the Late Cretaceous lack of polar glacial ice mass by a factor of -1.0 ‰ (Shackleton and Kennett, 1975) or -0.6 ‰ (Faure, 1991), then this value should be closer to +1.2 ‰ or +1.6 ‰, respectively. The +3.5 ‰ value of the dolomite of the Island Creek is approximately 2 ‰ heavy relative to a dolomite that would have formed as an authigenic precipitate from Late Cretaceous normal marine water. The calcite sample also appears to be heavy by at least this amount.

Table 2. Stable isotopic data, Island Creek Member of the Peedee Formation, Martin Marietta-Ideal Quarry, New Hanover County. Sampling horizons are indicated in columnar section (Figure 2).

Sample	Mineral	$\delta^{18}O_{PDB}$	$\delta^{13}C_{PDB}$
H8525	Dolomite	+3.7	+0.1
H8525	Calcite	+2.2	+0.6
H8526	Dolomite	+3.5	-0.5
H8527	Dolomite	+3.5	+0.1
H8528	Dolomite	+3.4	-0.3
H8529	Dolomite	+3.3	-0.3
H8530	Dolomite	+3.5	-0.5

The $\delta^{13}C$ (PDB) values center around -0.3 ‰ (Table 2). These values are somewhat lighter than expected for a dolomite that would have precipitated from shallow normal marine water and may indicate that some of the carbon in the dolomite was derived from an organic source.

DISCUSSION

Depositional Environment

The fauna and flora of the Island Creek Member seem to represent an autocthonous death assemblage. The delicate nature of most of the bioclasts indicates that transport was minimal beyond that caused by bioturbation. The fauna consists of at least 13 petrographic taxonomic components, and is almost entirely of small individuals less than 5 mm. The presence of echinoderm plates and calcareous nannofossils implies normal marine salinity; the other faunal and floral components could have tolerated a wider range of salinity (Heckel, 1972). The red algae imply shallow subtidal depths within the euphotic zone. The red algae and the bryozoans prefer clear water, and are usually, but not always, associated with a firm substrate. The general fineness of the sediment and the small size and delicate nature of the faunal components suggest low-energy conditions.

Although the exact nature of the organism responsible for the bioturbation is unknown, and no ichnotaxa could be identified, the pervasive bioturbation indicates a well circulated, oxygen-rich water column impinging upon the sediment surface at the time of deposition. However, the presence of fragile bone fragments and pyritized organic material suggests that reducing conditions developed below the sediment-water interface for at least short intervals of time during or after deposition, or intermittently during sediment accumulation. The oxygen isotope data suggests elevated salinity within the sediment pore water. The presence of ferroan carbonate also argues for the development of reducing conditions within the sediment. Sequence-keyed paragenesis of the Island Creek Member is shown in Figure 4.

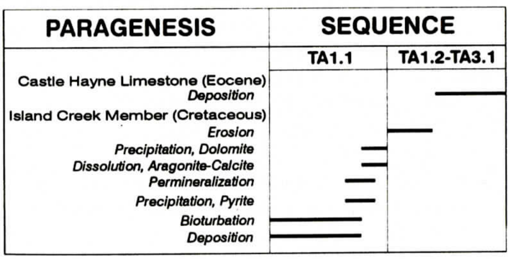


Figure 4. Sequence-keyed paragenesis of the Island Creek Member of the Peedee Formation.

Dolomite Formation

The oxygen isotope data suggest that: 1) evaporation had some influence in the evolution of the fluid from which the dolomite and calcite formed; 2) normal marine water was 2 ‰ heavy at the very end of the Cretaceous, relative to what has been reported in the literature for the Late Cretaceous; or 3) the dolomite precipitation and calcite diagenesis was not syndepositional but occurred at some later time (Fig. 4). No other evidence suggests the existence of evaporitic conditions during deposition of the Island Creek Member. The biota contained in the unit indicate normal open marine conditions. Little evidence exists to support a 2 ‰ heavier marine water for the end of the Cretaceous. Hsu *et al.* (1982) report a sudden shift toward heavy values for the K/T boundary clay at DSDP site 524, but this shortly recovers to the pre-boundary event trend. Perch-Nielsen *et al.* (1982), while noting the $\delta^{18}O$ shift at site 524 and at El Kef, Tunisia, failed to find similar shifts at other K/T boundary sites. In both cases the reported shifts are about 2 ‰ heavier. The only other times that such shifts occurred were during the Miocene, 20 to 25 Ma, and during the Pleistocene glacial events (Prentice and Matthews, 1988, Figure 2). If the dolomite is authigenically precipitated from normal marine water in either of these situations, then one would also expect the overlying Castle Hayne (Eocene) to likewise have experienced extensive dolomite precipitation as the Castle Hayne has a very open fabric with porosity as high as 50% (Dockal, 1986; Quinn and Dockal, 1994) and permeabilities ranging from 0.1 to 1,725 md (Thayer and Textoris, 1977). Yet the Castle Hayne, situated directly on top of the dolomite-bearing bed, entirely lacks dolomite indicating that dolomite precipitation predated Castle Hayne deposition (Figure 4). Hence, the oxygen isotope data suggests that the dolomite is related to elevated pore water salinity. The lack of dolomite in the Castle constrains dolomite formation to the period from onset of Island Creek deposition to onset of Castle Hayne deposition (Late Cretaceous to Middle Eocene).

Because the dolomite does not exhibit any of the petrographic characteristics that are indicative of replacement dolomite, the organic carbon must be part of the carbonate ions that formed the dolomite and not part of organic tissue inclusions that would have been trapped within the dolomite crystal lattice during replacement of a carbonate bioclasts. Carbonate that is carbon isotope light could have formed as a result of anaerobic oxidation of biogenic methane. Perch-Nielsen *et al.* (1982), however, report a sudden negative shift in the $\delta^{13}C$ (PDB) starting at the K/T boundary and continuing into the Early Tertiary from several K/T boundary sites. Hsu *et al.* (1982) postulated that the shift was the result of "...nearly total suppression of photosynthetic activities by planktonic organisms." The presence of pyrite and ferroan calcite argues in favor of anaerobic oxidation. The consistency of oxygen and carbon isotope values throughout the bed (Table 2) argue against drawing any analogy to K/T boundary observations for the origin of the dolomite, even though deposition of the Island Creek may be nearly coeval with K/T boundary events.

SUMMARY

Dolomitic sediments located disconformably above the Rocky Point Member of the Peedee Formation (Cretaceous) and disconformably below the Castle Hayne Limestone (Eocene) at the Martin Marietta-Ideal Cement Quarry are designated the Island Creek Member of the Peedee Formation. The Island Creek Member contains a characteristic upper Maastrichtian nannofossil flora, which appears to correlate to Cretaceous nannofossil zones CC 25-CC 26. The Island Creek Member is predominantly an olive gray (5 Y 4/1), well sorted, very fine to fine grained, poorly indurated, bioturbated, argillaceous, dolomitic quartz wacke (sensu Dott, 1964). The fauna and flora suggest deposition in normal marine, aerobic environment, below storm wave base. Carbon and oxygen isotopes and crystal morphology of post-depositional, pore-filling dolomite indicate that elevated salinity existed in the sediment for a short time after deposition of the Island Creek.

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REFERENCES CITED

Alexopoulos, J.S., Grieve, R.A.F. and Robertson, P.B., 1988, Microscopic lamellar deformation features in quartz: discriminative characteristics of shock-generated varieties. Geology, v. 16, p. 796-799.

Allan, J.R., and Wiggins, W.D., 1993, Dolomite reservoirs: geochemical techniques for evaluating origin and distribution. American Association of Petroleum Geologists, Continuing Education Course Note Series #36, 129 p.

Baum, G.R., 1977, Stratigraphic framework of the middle Eocene to lower Miocene formations of North Carolina (unpublished Ph. D. thesis): University of North Carolina at Chapel Hill, Chapel Hill, 139 p.

Cunliffe, R.E., 1968, Petrology of the Cretaceous Peedee Formation and Eocene Castle Hayne Limestone in northern New Hanover County (unpublished M.S. thesis): University of North Carolina at Chapel Hill, Chapel Hill, 128 p.

Dickson, J.A.D, 1966, Carbonate identification and genesis as revealed by staining: Journal of Sedimentary Petrology, v. 36, p. 491-505.

Dockal, J.A., 1986, Cements and related diagenetic features of the Castle Hayne Limestone, East Coast Limestone Quarry, Pender County, North Carolina; *in* Harris, W.B., Zullo, V.A. and Otte, L.J., (eds.), Eocene carbonate facies of the North Carolina Coastal Plain; *in* Textoris, D.A. (ed.) SEPM Guidebooks, Southeastern United States, Midyear Meeting, Raleigh, NC, p. 277-284.

Dott, R.H., 1964, Wacke, graywacke and matrix-what approach to immature sandstone classification?: Journal of Sedimentary Petrology, v. 34, p. 625-632.

Faure, G., 1991, Principles and Application of Inorganic Geochemistry: New York, Macmillian, 626 p.

Harris, W.B., 1975, Stratigraphy, petrology, and radiometric age (Upper Cretaceous) of the Rocky Point Member, Peedee Formation, North Carolina (unpublished Ph.D. thesis): University of North Carolina at Chapel Hill, Chapel Hill, 190 p.

Harris, W.B., 1978, Stratigraphic and structural framework of the Rocky Point Member of the Cretaceous, Peedee Formation: Southeastern Geology, v. 19, p. 207-229.

Harris, W.B., Baum, G.R., Wheeler, W.H., and Textoris, D.A., 1977, Lithofacies and structural framework of the Castle Hayne Limestone, North Carolina: Geological Society of America, Abstracts with Programs, v. 9, p. 144-145.

Harris, W.B., Zullo, V.A. and Otte, L.J., 1986, Road log and description of field trip stops; *in* Harris, W.B., Zullo, V.A. and Otte, L.J., (eds.), Eocene carbonate facies of the North Carolina Coastal Plain; *in* Textoris, D.A. (ed.) SEPM Guidebooks, Southeastern United States, Midyear Meeting, Raleigh, NC, p 311-332.

Heckel, P.H., 1972, Recognition of Ancient Shallow Marine Environments; *in* Rigby, and Hamblin, (eds.), Recognition of Ancient Sedimentary Environments: Society of Economic Paleontologists and Mineralogists, Special

Publication No. 16, p. 226-286.

Hsu, K.J., McKenzie, J.A., and He, Q.X., 1982, Terminal Cretaceous environmental and evolutionary changes; *in* Silver, L. T., and Schultz, P. H. (eds.), Geological implications of impacts of large asteroids and comets on the Earth: Geological Society of America Special Paper 190, p. 317-328.

Land, L.S., 1980, The isotopic and trace element chemistry of dolomite: the state of the art; *in* Zenger, D.H., Dunham, J.G., and Ethington, R.L. (eds.), Concepts and Models of Dolomitization: Society of Economic Paleontologists and Mineralogists, Special Publication 28, p. 87-110.

Land, L.S., 1985, The origin of massive dolomite: Journal of Geologic Education, v. 33, p. 112-125.

McLaurin, B.T., 1995, Stratigraphic and sedimentological analysis of the Paleocene Beaufort Group, Lenoir and Craven Counties, North Carolina (unpublished M.S. thesis, University of North Carolina at Wilmington, Wilmington, 80 p.

McLaurin, B.T. and Dockal, J.A., 1995, Characterization of dolomite within the Beaufort Group (Paleocene), Lenoir and Craven Counties, North Carolina: Geological Society of America, Abstracts with Programs, v. 27, p. 73.

Perch-Nielsen, K., McKenzie, J.A., and He, Q.X., 1982, Bio-and isotope-stratigraphy and the "catastrophic" extinction of calcareous nannoplankton at the Cretaceous? Tertiary boundary; *in* Silver, L.T., and Schultz, P.H., (eds.), Geological implications of impacts of large asteroids and comets on the Earth: Geological Society of America Special Paper 190, p. 353-371.

Pierre, C., Ortlieb, L., and Person, A., 1984, Supratidal evaporitic dolomite at Ojo de Liebre Lagoon: mineralogical and isotopic arguments for primary crystallization: Journal of Sedimentary Petrology, v. 54, p. 1049-1061.

Prentice, M.L. and Matthews, R.K., 1988, Cenozoic ice-volume history: development of a composite oxygen isotope record: Geology, v. 16, p. 963-966.

Quinn, J., and Dockal, J.A., 1994, Porosity of the Castle Hayne Limestone (Eocene), Carolina Beach, New Hanover County, North Carolina: Geological Society of America, Abstracts with Programs, v. 26, p. 59.

Shackleton, N.J. and Kennett, J.P., 1975, Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: oxygen and carbon isotope analyses in DSDP Sites 277, 279, and 281; *in* Kennett, J.P., Houtz, R.E., *et al.* (eds.), Initial reports of the Deep Sea Drilling Project, Volume 29: Washington, D.C., U.S. Government Printing Office, p. 743-755.

Short, N.M., and Gold, D.P., 1996, Petrography of shocked rocks from the central peak at the Manson impact structure; *in* Koeberl, C., and Anderson R.R. (eds), The Manson impact structure, Iowa: anatomy of an impact crater: Geological Society of America Special Paper 302, p. 245-265.

Sohl, N.F., and Owens, J.P., 1992, Cretaceous stratigraphy of the Carolina Coastal Plain; *in* Horton, Jr., J.W. and Zullo, V.A. (eds.), The geology of the Carolinas: Knoxville, University of Tennessee Press, p. 191-220.

Thayer, P.A., and Textoris, D.A., 1977, Faunal and diagenetic controls of porosity and permeability in Tertiary aquifer carbonates, North Carolina: North Carolina Department of Natural and Economic Resources, Division of Earth Resources, Geology and Mineral Resources Section, Special Publication 7, 35 p.

Wilson, P.A. and Opdyke, B.N., 1996, Equatorial sea-surface temperatures for the Maastrichtian revealed through remarkable preservation of metastable carbonate: Geology, v. 24, p. 555-558.

Book Review

***From Top To Bottom,* by Leonard Alberstadt; Eggman Publishing, Inc., 3012 Hedrick Street, Nashville, TN 37203, 201 pages plus Appendix, softbound; $14.95; ISBN 1-886371-24-5**

I have never read anything quite like this detailed and painful accounting of a Geology department that languished for a century. Over the space of 200 pages and 28 chapters, the author, a long time member of the Geology Department at Vanderbilt University, tells a very sad story. The focus of this book is on the time period of 1875 to 1980 at Vanderbilt. After an auspicious beginning in the 1870s, a Vanderbilt Geology faculty member crossed wires with university administration over the subject of evolution and Geology never recovered. Geology granted its last Ph.D. in 1905 and well before that time it had been relegated to low priority status. While other sciences grew and prospered, Geology faculty numbered only two until 1929 and were no greater than three until 1962. The department was threatened with extinction in the late 1960s. Efforts by faculty at reestablishing a Ph.D. program in Geology were repeatedly rebuffed.

Over the first 100 years, geology remained a small department whose central purpose was to teach what is now considered to be freshman geology (physical geology and historical geology). There were a number of local political reasons for the lack of growth. One was the poor political skill of its faculty. For decades, the faculty insisted that chemistry be a prerequisite to taking classes in geology. This prerequisite had intellectual justification, but it served to keep enrollments in geology depressed. Without large enrollments, it was probably impossible to convince a university that is dominated by its medical school to allow a non-medically related science to prosper. Also, a school that principally attracts students with premedical inclinations cannot expect great student interest in geology under the best of conditions. Even if the faculty had played their political cards properly, it is unclear whether they would have fared much better. Vanderbilt University was just not a conducive environment to develop a nationally competitive research program in Geology.

Reading this book, one wonders why the author, who likely would have worked to improve any department in which he took a position, didn't leave Vanderbilt early in his career. The lack of interest in geology shown by the university was clear. In the sixties, seventies and part of the eighties, geology faculty were in fairly high demand in this country. Other institutions were significantly expanding their faculty in geology and providing financial backing for research facilities. Other faculty members moved from Vanderbilt to more geologically friendly institutions with apparently very little regret. In the end, one feels some sadness for the many faculty who worked to improve the research climate of Geology at a university that had no desire to achieve prominence in this field.

In this book, virtually nothing is mentioned of the time period since 1980. Clearly this time period has been beneficial to the department. Through tables contained in the book, it appears that the number of Geology faculty increased from four in 1976 to nine in 1995. One might imagine that this increase was accompanied by growth in space, equipment and research. Perhaps the author chose not to discuss this time period out of respect for those in the department today. However, the story contained in this book might have been less somber if the author would have included some additional information on this period of growth.

To some extent, the book reads like a polemic on the need for a Ph.D. program in Geology at Vanderbilt University. One gets the strong impression that the author feels that if there was such a program, many of the ills in the department, which have a strong historical base, would be solved. The author argues that Vanderbilt compares favorably with top notch private schools in virtually every aspect of the sciences except Geology. There is some truth to this argument. However, in the current economic context of universities across the nation, this is not justification enough for creating a new Ph.D. program. Beset with severe financial constraints, universities are looking at ways to cut costs, not add to them. Under these conditions, many geology departments are facing difficulties. The attitude of Vanderbilt's administration toward Geology in its first century might be mimicked by many universities in the near future.

With the caveat that this book is bleak in tone, I recommend it to anyone interested in the evolution of Geology as a discipline in the United States. Through the detailed history of Geology at Vanderbilt, one can glean information on the general state of Geology at the turn of the 20th century. The book also provides a window into cultural attitudes about Geology in the southern United States. It is a well written book that many geologists will find worth reading.

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